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AN ASSESSMENT OF THE CRASH FIRE HAZARD OF LIQUID HYDROGEN FUELED AIRCRAFT

by

ARTHUR D. LITTLE, INC.

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final report prepared for

NATIONAL AERONAUTICS & SPACE ADMINISTRATION
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1. EXECUTIVE SUMMARY

1.1 BACKGROUND

Over the past years, there has been an interest in the development of future aircraft fueled with liquid hydrogen (LH_2). Several aircraft manufacturers have performed design studies on LH_2-fueled airplanes. NASA was interested in identifying any technological gaps which might need follow-on work after a comparison and safety assessment was made. The fuels for comparison with LH_2 were specified to be liquid methane (LCH_4), Jet A, JP-4 and gasoline. An important question, crucial to any future decision to build a LH_2-fueled aircraft, is the relative crash fire hazards associated with LH_2 fuel.

Consequently, NASA issued a request for proposals on "An assessment of the Crash Fire Hazard of Liquid Hydrogen Fueled Aircraft." Two proposals were accepted by NASA. The Arthur D. Little, Inc. work is described in this report; the parallel work done for NASA by the Lockheed Corporation is the subject of a separate report. The two projects were done independently although Arthur D. Little, Inc. used Lockheed designs for future LH_2 and LCH_4 fueled aircraft as a basis for the evaluation. This choice was based on the large amount of design work already done and published by Lockheed on these concepts.

1.2 SCOPE OF WORK

The program consisted of three tasks in addition to a reporting task.

Task I. State-of-the-Art Review.

- To collect and evaluate data relating to the hazardous properties of liquid hydrogen in comparison to those of LCH_4, Jet A, JP-4, and gasoline.

- To review crash fire data from Jet A, JP-4 and gasoline aircraft accidents.
- To review recent studies and proposals for liquid hydrogen fueled aircraft by major aircraft manufacturers.

Task II. Crash Scenario Evaluation and Modeling

- To evaluate four general crash scenarios:
    1) A nonnormal landing or ground accident which results in fuel system insulation damage and/or fuel system damage permitting liquid hydrogen to vent, escape, leak or run out of a punctured tank or broken line.
    2) A survivable "crash" landing or failed "takeoff" where damage to fuel tankage or lines results in a massive release of liquid hydrogen after the aircraft has come to rest.
    3) A survivable "crash" landing or failed "takeoff" where damage to fuel tankage or lines results in a massive release of liquid hydrogen upon impact and during aircraft deceleration.
    4) A catastrophic crash resulting in the maximum rate of energy release in the form of a conflagration and/or explosion.
- To determine the theoretical characteristics or models of these scenarios with liquid hydrogen, in comparison with liquefied natural gas and methane, and conventional hydrocarbon fuels (such as Jet A and JP-4). The comparative hazards of each fuel evaluated shall be determined. The effect of fuel tank location and ignition sources and other relevant parameters associated with cryogenically fueled aircraft designs recently proposed by major aircraft manufacturers shall be incorporated into this study.

Task III. Comprehensive Review and Analysis

- To present analytical models applicable to the various fire scenarios and compare the relative crash fire effects for all the fuels.
- To identify technological gaps and specific unknowns and uncertainties that limit the depth of this study.
- To suggest areas for follow-on research and experiments to provide technology and data supplemental to this study and applicable to the design and development of liquid hydrogen fueled aircraft.

1.3 GENERAL APPROACH

To meet the objectives of this study, we conducted an extensive evaluation of available information on past crash fire accident descriptions as well as on the potential designs available for cryogenic and conventional fueled aircraft. After selecting a set of designs based on equivalent passenger capacity and range for our comparative analysis, we evaluated a broad range of potential hazards associated with realistic types of crash damage. The four scenarios given to us by NASA in the Statement of Work were used to categorize crash events in general terms. Rates and quantities of fuel release were identified for the LH_2, LCH_4 and conventional fueled aircraft.

Next, we reviewed available hazard models for describing potential consequences of such releases for the various fuels and crash scenarios. At this point, we identified the most significant hazards and concentrated our efforts in a comparative analysis of the consequences expected for the various fuels. Finally, we performed a comparative evaluation and identified some areas where additional work appears to be needed prior to an active decision to proceed with a LH_2-fueled aircraft.

In this report, the state-of-the-art task results are distributed by subjected matter in the appropriate sections. Section 2 describes available design concepts for LH_2 fueled and comparable LCH_4 and conventional fuel aircraft and discusses our rationale for selecting the designs on which our comparative evaluation is based. Section 3 presents and evaluates available historical crash fire data. These data, for the selected aircraft configurations, are utilized in Section 4 to characterize accident scenarios. In Section 5, we discuss possible hazards and identify the more significant hazards for comparative analyses.

The analysis and comparison of hazards due to fireball formation are presented in Section 6; pool fire hazards are evaluated in Section 7. Section 8 summarizes the main results of the comparative evaluation and presents recommendations for future work. Supporting information and analyses are presented in Appendices A to C.

1.4 CONCLUSIONS AND RECOMMENDATIONS

In this study, we compared crash fire hazards of mission equivalent, 400 passenger, Mach 0.85, 5500 n. mile range aircraft for three types of fuel. These fuels were liquid hydrogen, liquid methane, and conventional jet fuel. The two cryogenic-fueled designs had tanks located in the fuselage; the conventional fuel aircraft had wing fuel tanks. All the designs were based on published Lockheed studies.

For purposes of comparison, we considered four crash scenarios ranging from minor releases to a catastrophic crash. In each scenario, the potential fuel-release and crash fire consequences were compared for the three types of fuels.

Our basic conclusion is that the crash fire hazards are not significantly different when compared in general for the three fuels, although some fuels showed minor advantages in one respect or another. Specifically:

- For fireball post crash scenarios, LH_2 showed relatively lower hazard zones at grade than did conventional fuels and LCH_4 (in that order). This effect is apparent whether the comparison is made on the basis of total fuel volume released or on the basis of equivalent chemical energy content of the fuel released. This is due to the rapid burning of the hydrogen, the smaller fireball size, and the lower emissivity of the hydrogen flame.

- For fuel releases resulting in pool fires, LH_2 also produces smaller hazard zones than the other fuels, on either a volume or energy content comparative basis except for the largest spill sizes where the hazard zone may be slightly higher than that for conventional fuel - but still substantially less than that for LCH_4. Again, the LH_2 fire burns out very quickly, has a smaller diameter (although taller) flame and a lesser emissive power except at very large spill sizes.

- Dispersing aerosol is potentially a problem for all three fuels. Aerosol formation was not treated comparatively because it is so dependent on the specifics of particular crash conditions.

- For the two cryogenic fuels, downwind dispersion of vapors from unignited fuel spills is a potential problem. One might expect LCH_4 to be more likely to disperse downwind near grade; LH_4 might be more likely to rise. However, with aerosol formation, both dispersing clouds could remain near grade.

- Because of the wider flammability limits, more fuel is likely to be flammable at any time in a dispersing LH_2 vapor cloud than in an equivalent LCH_4 vapor cloud. However, this increases the chance of earlier ignition in a dispersing LH_2 cloud and may reduce the extent of downwind vapor fire damage.

- Smaller spills of LH_2 and LCH_4 are likely to disperse as neutrally buoyant plumes.

- Considerable uncertainty exists in prediction of downwind dispersion distances for large LCH_4 spills because of limited experimental data and the complexity of the physical effects involved in developing a theoretical model. Far less data are available for LH_2 spills.

- In severe crashes, fire is so likely that theoretical flammable vapor dispersion with delayed ignition is not considered a credible threat at large distances from the crash.

- LH_2 is more likely to cause blast effects due to accumulation and ignition in confined spaces. This problem can be minimized by careful design, monitoring, provision of inerting systems, and design with secondary barriers to contain small leaks.

In summary, our comparative evaluation for historically observed crash damage scenarios applied to mission equivalent aircraft shows that LH_2 offers survivability benefits in most cases where a fire occurs rapidly. These advantages and disadvantages in other respects are relatively minor and difficult to quantify. However, from a crash fire hazard standpoint, LH_2 does not appear to be a significantly more hazardous fuel than conventional jet fuels and LCH_4. In some respects, it offers lesser hazards. Thus, pending some future research and development work, we see no crash fire hazard situations which should discourage development of a LH_2-fueled aircraft.

From our evaluation, we recommend that additional safety studies be performed to clarify some of the remaining uncertainties relating to LH_2 hazards. In particular:

- Additional dispersion and fire tests would be desirable to confirm the conclusions drawn in this study, which are based on the current state-of-the-art. For example, pool fire tests with an instrumented fuselage can be conducted to test the validity of our predictions in Section 7.

- Comparisons between future LH_2 tests and planned LCH_4 (LNG) tests, under DOE sponsorship at Jackass Flats, Nevada, should be made.

- Second generation fire and dispersion models should be developed, based on theory and results of experiments.

Further, should the development of a LH_2 aircraft proceed, some technological improvements should be given priority; for example:

- Further studies to develop optimum design and systems for LH_2 aircraft are needed. Crashworthiness should be an important consideration in design.

- Since component reliability is very important in preventing minor leaks with potential for creating a serious incident or accident in a LH_2 aircraft, attention should be focussed on further development work on the following components:

  - Less expensive pumps ($5,000 range)

  - Improved pump seals with a longer operating life (present seals are designed for only a few hours of operation)

  - Evaluation of new types of fuel transfer systems to minimize the change of any leakage (pump seals, valve packings, etc.)

  - Improved lightweight and strong storage systems

  - Optimized LH_2 combustors

2. AIRCRAFT SYSTEM SELECTION

2.1 INTRODUCTION

The assessment of the crash fire hazard of LH_2-fueled, subsonic, commercial aircraft requires the use of aircraft concepts which represent the most probable missions and configuration of this post 1990-1995 transportation system. Because no liquid hydrogen fueled aircraft exist, the crash hazard analysis must be based upon preliminary designs of practical commercial :rcraft using this fuel. The purpose of this section is to identify, from published information, the most viable concept for the liquid hydrogen-fueled aircraft and a concept for "comparable" LCH_4 and conventional fuel aircraft.*

In the following paragraphs, first we review briefly the information available in the literature on various LH_2 aircraft concepts. Secondly, we define the anticipated mission of a LH_2 aircraft. Thirdly, we select three aircraft designs having the same mission but fueled by LH_2, LCH_4 and conventional fuel.

2.2 REVIEW OF DATA ON LH_2 AIRCRAFT CONCEPTS

In the 1970's the major U.S. commercial aircraft manufacturers gave serious consideration to alternate aircraft fuels with particular interest centering on liquid hydrogen. Much of this work was self-sponsored and none, but the most general results, are available in open literature. Beginning in 1973, however, NASA/Langley sponsored a series of studies on liquid hydrogen fueled subsonic commercial aircraft which dealt with the following major topics:

1. LH_2 Aircraft and Comparison JAF Aircraft (2.1, 2.2)[f]
2. LH_2 Aircraft Fuel System (2.3)
3. LH_2 Aircraft Airport Requirements (2.4, 2.5)
4. LCH_4 Aircraft and Comparison LH_2 and JAF Aircraft (2.6)

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*In this section, we do not distinguish between the conventional fuels (JP-4, gasoline, kerosine and Jet A) since their corresponding fuel systems are essentially similar.

[f]Numbers in brackets denote references which are presented in Section 9.

Lockheed performed each of these studies and Boeing only the third study, duplicating the Lockheed work. Together they are the definitive data source on the LH_2, JAF and LCH_4 fueled subsonic aircraft.

In-house supported studies were also conducted by both Boeing[2.7,2.8] and McDonnell Douglas[2.9]. Their most general results, presented in papers, testimony and brochures, have been made available to us.* These do not present sufficient data on the LH_2 aircraft configuration nor do they provide information for any comparison with JAF fueled aircraft. Further, LCH_4 fueled aircraft is not given any consideration in the available material. Table 2.1 summarizes the appropriate information and references.

The principal configuration factors are the size and shape of the aircraft and the locations within the aircraft of the passengers, stored fuel and engines. Each type of fuel may require its own particular aircraft configuration. In one of its earlier studies, Lockheed[2.3] evaluated eight LH_2 fuel location concepts. Four of these included fuel in the fuselage, and two each for fuel in pods and fuel in wing. Their results indicated that the most favored configuration was fuel in the fuselage located fore and aft of the passenger compartment. This result was recently confirmed by Boeing[2.12] and McDonnell Douglas[2.14].

The above noted result was also obtained when Lockheed conducted the methane fuel study[2.15]. Further, in both the LH_2 and the LCH_4 fuel studies, the second most favored fuel configuration was the fuel located in twin pods mounted onto and above the wings. This latter configuration more nearly conforms to JAF aircraft with fuel located in the wings.

The LH_2 placement fore and aft, as indicated above, leaves unresolved the federal regulations requiring passage between the cockpit and passenger spaces of the aircraft.

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*We also interviewed company representatives on the telephone (see References 2.12 and 2.14).

TABLE 2.1

SUMMARY OF INFORMATION AVAILABLE IN THE OPEN LITERATURE FOR PROJECTED LH_2, LCH_4 AND JAF FUELED AIRCRAFT

		LOCKHEED			BOEING			MCDONNELL DOUGLAS		
		LH_2	LCH_4	JAF	LH_2	LCH_4	JAF	LH_2	LCH_4	JAF
MISSIONS STUDIED	PAX RANGE (n mi) MACH No.	130-800 1500-10000 0.8-0.9	130-400 1500-10000 .85	400 3000-5500 .85	200 3000 (.85)	N/A N/A N/A	N/A N/A N/A	600 5200 .85	N/A N/A N/A	600 5200 .85
CONFIGURATION	No. Studied Fuel System Data	8 A	3 A	1 N/A	1 N/A	N/A N/A	N/A N/A	1 N/A	N/A N/A	1 N/A
PERFORMANCE DATA		A	A	A	N/A	N/A	N/A	N/A	N/A	N/A
REFERENCES*		2.1, 2	2.4, 5	2.2	2.7, 8	N/A	N/A	2.9	N/A	2.9

SYMBOL	DESCRIPTION
A	Available in open literature
N/A	Not available or not applicable
PAX	Passengers
( )	Not available, but most probable value is given
n mi	Nautical Miles
LH_2	Liquid hydrogen fueled aircraft
LCH_4	Liquid methane fueled aircraft
JAF	Jet A fueled aircraft

* References contained at the end of this report.

In 1973, Boeing also considered a 747 passenger aircraft modified for LH_2 fuel[2.10]. This modified aircraft has a passenger capacity for 369 passengers and a range of 5100 nautical miles. The fuel configuration for this concept was for LH_2 within the fuselage in tanks located over the passenger compartment. Boeing was interviewed[2.12] for their current views on the use of a modified 747. Boeing no longer considers this to be a viable concept because of the extensive structural modifications of the aircraft that are needed. In addition, the 747 utilizes material and aerodynamic technologies of the late 1960's. On the other hand, the LH_2 aircraft is not expected to develop as a complete transport system until the early 1990's. Thus, the anticipation of the new technologies that will be applicable at that time will make any modified 747 aircraft obsolete. This argument applies to the other wide body aircraft such as the Lockheed L-1011 and the McDonnell Douglas DC-10.

2.3 ANTICIPATED MISSION OF A LH_2 COMMERCIAL AIRCRAFT

The primary factors required in the comparative crash fire hazard analysis are the stored fuel quantities, their location within the aircraft and their proximity to the passenger compartments, the conditions of the fuel and the deposition of the fuel system lines in the aircraft, i.e., power plant feed, loading and vent lines, etc. These factors vary significantly depending on the type of fuel and the aircraft mission.

To examine the effect of the fuel type, it is desirable to consider aircraft having the same mission. To do so, we defined first the anticipated mission of a LH_2 aircraft. The principal mission parameters of a subsonic commercial aircraft are the passenger capacity, range and speed. They are discussed below.

2.3.1 Passenger Capacity

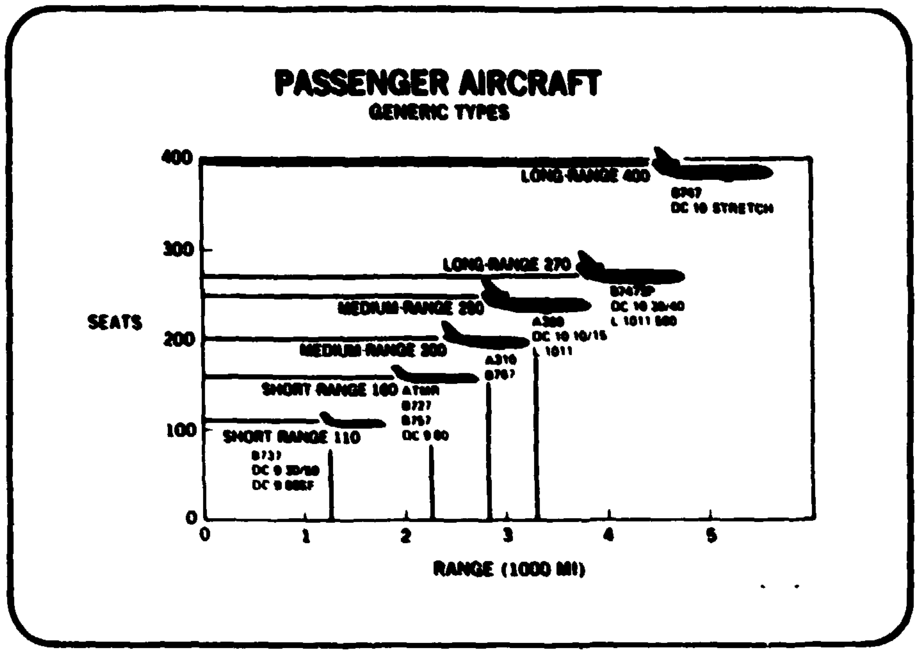
The passenger capacity (PAX) establishes the mission payload. It includes the passengers, their baggage, the crew and whatever is needed for their sustinance and survivability.

The success of the commercial jet aircraft in the early 1960's brought about a rapid expansion in passenger service. However, the limited passenger capacity of these aircraft (100 to 200 passengers) resulted in increased air traffic at airports which subsequently led to traffic congestion and delays in departures and arrivals.

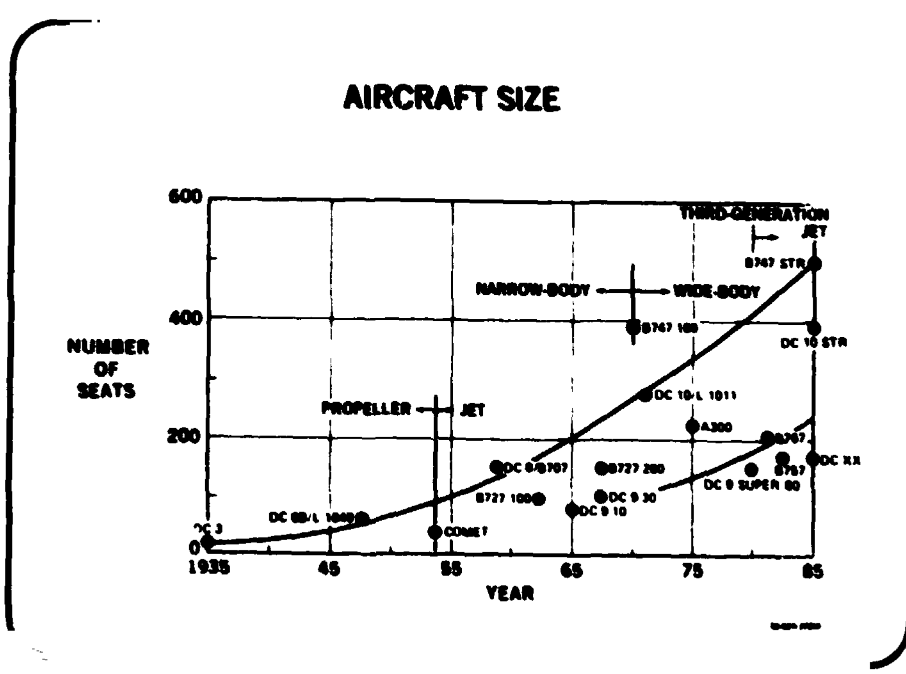
Traffic forecasts prepared by the air carriers in the mid 1960's indicated the increasing air traffic congestion at airports would be alleviated by the introduction of commercial transport aircraft of greater passenger-carrying capacity. It was essential that such aircraft should not be restricted to operation from those airports with very long runways. The recognized need led to the development and manufacture of the Boeing 747, Lockheed L1011 and McDonnell Douglas DC-10. These aircraft made their debut in 1970-1972 time period and have been in extensive commercial service since that time.

Since their inauguration, the respective manufacturers have built these aircraft in a number of series to meet a variety of commercial air service requirements. In general, however, this group of wide-bodied aircraft have a nominal capacity of 400 passengers, a range of 2300 to 5000 miles with maximum fuel load, and a cruising speed of Mach 0.82 to 0.85. The studies that have been conducted for the liquid hydrogen fueled aircraft have been based on this set of requirements, and have been demonstrated to be logistically viable for a present and future commercial transport system.

The passenger capacities of commercial jet aircraft have shown an upward trend since the introduction of the Douglas DC-3 in 1935. This trend is illustrated in Figure 2.1 for a number of typical aircraft in the 1935-1980 period and with projections to 1985[2.11]. The factors promoting this trend, which include direct operating costs and the annual market growth in revenue passenger miles, are probably not reversible. Thus, the viability of the liquid hydrogen fuel for commercial aircraft would depend on the comparability of liquid hydrogen at large (400 or more) PAX capacities.



(a)



(b)

FIGURE 2.1

PASSENGER AIRCRAFT CAPACITIES

Source: Robert E. Hage (See Reference 2.11)

The Lockheed studies have considered capacities from 400 to 800 PAX, but most of the detailed analysis and comparison have been for a 400 PAX aircraft. Boeing[2.7,2.8] and McDonnell Douglas[2.9] favor 200 and 700 PAX missions, respectively for the LH_2 fueled aircraft.

Based upon the trends, a 400 PAX aircraft is not unreasonable and may be on the low side in the post 1990-1995 time frame. Further, the best available design projections are those prepared by Lockheed for a 400 PAX aircraft. These findings suggest that the 400 PAX aircraft is acceptable for the current study.

2.3.2 Range

Commercial aircraft ranges are classified as short range (less than 2,500 n mi), medium range (between 2,500 and about 4,000 n mi) and long range (greater than 4,000 n mi). The aircraft size is greatly dependent upon range because of the direct relationship between the fuel requirements and range for a given payload.

According to Hage[2.11], the passenger aircraft market between 1980 and 1999 will experience a demand for 7,000 aircraft of which 30 percent will be for medium-range aircraft and 25 percent for long-range aircraft.

The longer the range of an aircraft, the more versatile it is in the air transportation system. Greater range permits longer flights, more flexibility to avoid severe weather conditions, and ability to hold over airports when traffic conditions and/or weather delay landing of the aircraft. Also, where mechanical failures of an aircraft scheduled for flight require a replacement aircraft, an alternate with long range capability is a more probable replacement than one with short range capability.

Witcofski[2.13] has shown that range may be an important factor in the viability of the LH_2 aircraft. His comparison of the mission energy consumption of the LH_2-fueled aircraft with Synjet fueled aircraft shows a savings of from 2 to 33 percent, with energy savings increasing with range.

The above arguments serve only to indicate that if the LH_2 aircraft comes into being, it will probably be designed with a long range capability. Lockheed has considered aircraft designs with range capabilities between 1,500 and 10,000 n mi. However, it has concentrated its design efforts on the 5,500 n mi range aircraft. This appears to be a reasonable choice at the present stage of development.

2.3.3 Speed

The average speed of subsonic commercial jet aircraft has been increasing very gradually in the last 20 years from about 440 n mi/hr (DC-8, B-707) to about 470 n mi/hr (B-747, A-300). The latter represents a Mach no. of about 0.8 at 35,000 ft. altitude. This trend though still rising probably has an asymptote at Mach 0.9. The choice of Mach 0.85 by Lockheed for the speed of the most favored mission appears reasonable.

2.4 AIRCRAFT SELECTED FOR STUDY

Based on the information presented above, we conclude that:

- Under NASA contracts, Lockheed has conducted and published the definitive source material for subsonic aircraft fueled with LH_2, LCH_4 and JAF. The studies are the most thorough and comprehensive available in which the performance of aircraft designed for these specific fuels are compared on an identical mission basis.

- Lockheed studied a large range of aircraft missions. The most favored and those developed in greatest detail are for aircraft with 400 passengers with a range of 5500 nautical miles at a speed of Mach 0.85.

- The most favored aircraft configuration of the LH_2 and LCH_4 fueled aircraft is with the fuel located in the fuselage, fore and aft of the passenger compartment. This result was reached independently by Lockheed, Boeing and Douglas aircraft manufacturers.

- The second most favored configuration of the LH_2 and LCH_4 fueled aircraft is with the fuel located in two wing mounted pylons, i.e., external fuel tanks mounted above the wings. This configuration has a greater similarity to the jet fueled aircraft

configuration for crash hazard analysis than the fuel-in-fuselage configuration.

- The Lockheed studies are the only ones available in which the LH_2 and LCH_4 fuel systems are sufficiently detailed for use in the crash hazards study.

Accordingly, for the purpose of this study, we selected the primary LH_2, LCH_4, and JAF fueled aircraft configurations developed by Lockheed for the 400 passenger, 5500 nautical mile and Mach 0.85 speed, mission. The main specifications of these aircraft are summarized in Tabl^ 2.2. The main features of their fuel system are described in Appendix A. Additional description of the entire aircraft are given in References (2.1 to 2.4 and 2.6).

TABLE 2.2
SPECIFICATIONS OF COMPARABLE HYDROGEN, METHANE AND JET A FUELED TRANSPORT AIRCRAFT

(400 Passengers · 10 190 km (5 500 n.mi.) · Mach 0.85)

		Hydrogen	Methane Configuration 1	Jet A
Gross Wt.	kg (lb)	168 800 (372 205)	224 000* (493 900*)	232 060 (511 600)
Total Fuel Wt.	kg (lb)	25 600 (56 457)	69 040 (152 200)	84 780 (186 900)
Block Fuel Wt.	kg (lb)	21 620 (47 664)	58 500 (129 000)	72 350 (159 500)
Operating Empty Wt.	kg (lb)	103 300 (227 748)	115 030 (253 600)	107 370 (236 700)
Aspect Ratio	-	9 (9)	9 (9)	9 (9)
Wing Area	m^2 (ft^2)	297 (3 195)	417 (4 490)	380 (4 093)
Sweep	rad (deg)	0.524 (30°)	0.524 (30°)	0.524 (30°)
Span	m (ft)	51.8 (170)	61.3 (201.0)	58.5 (192)
Fuselage Length	m (ft)	65.7 (215.6)	61.4 (201.3)	60.0 (197.0)
L/D Cruise	-	17.36 (17.36)	19.11 (19.11)	19.13 (19.13)
SFC Cruise	$\frac{kg}{hr}$/daN (lb/hr/lb)	0.206 (0.202)	0.502 (0.492)	0.615 (0.603)
Initial Cruise Alt	m (ft)	11 582 (38 000)	11 582 (38 000)	(11 582) (38 000)
Wing Loading	kg/m^2 (lb/ft^2)	569 (116.5)	537 (110.0)	610 (125.0)
T/W	N/kg	3.20 (0.326)	2.94 (0.300)	3.20 (0.325)
Thrust Per Engine	N (lb)	134 990 (30 350)	164 750 (37 040)	185 040 (41 600)
FAR T.O. Distance	m (ft)	2440 (8 006)	2377 (7 804)	2431 (7 976)
FAR Landing Distance	m (ft)	1768 (5 799)	1524 (5 001)	1584 (5 197)
Engine Out Climb Grad	-	0.030 (0.030)	0.030 (0.030)	0.035 (0.0305)
Approach Speed	m/s KEAS	71.2 (138.4)	63.6 (123.7)	65.5 (127.4)
Weight Fractions				
Fuel	%	15.17 (15.17)	30.82 (30.82)	36.53 (36.53)
Payload	%	23.64 (23.64)	17.82 (17.82)	17.20 (17.20)
Structure	%	32.39 (32.39)	29.25 (29.25)	26.32 (26.32)
Propulsion	%	9.07 (9.07)	6.74 (6.74)	5.37 (5.37)
Price – Millions	$\$10^6$ ($\$10^6$)	43.39 (43.39)	47.45 (47.45)	44.53 (44.53)
DOC Cents/Seat n.mi.	cents/seat km (cents/seat n.mi.)	0.8[illegible] (1.609)	0.802 (1.486)	0.907 (1.679)
Energy Utilization	kJ/seat km	637	717	759

(*Fuel system, insulation and tank weights not finalized here.)

3. HISTORICAL AIRCRAFT ACCIDENT DATA

3.1 INTRODUCTION

In this section, we present a brief review of historical aircraft accident data to identify possible characteristics of importance to our study. Examples of such characteristics include questions such as: has a fire always occurred when a large amount of fuel was released? how frequent are fuel tank explosions in an aircraft engulfed by flames? how often is the passenger compartment breached thereby exposing the passengers directly to the flames from a fuel pool fire? what is the relative susceptibility of various sections of the aircraft where fuel may be located (such as wing for JAF fuel and fuselage for cryogenic fuels)? The answers to these questions will be used to guide our hazard assessment.

In our review of the published literature on accident data, we found that attention has been placed mainly on identifying various accident scenarios and their causes. However, some of the questions of interest to us were not specifically addressed. In the following paragraphs, we first review aircraft accident scenarios in general to highlight the importance of the four generic types that will be addressed in this program (as specified in the Scope of Work). Secondly, we survey a number of data sources for their utility to further characterize these scenarios and answer the questions raised above.

3.2 HISTORICAL TRENDS IN AIRCRAFT ACCIDENTS

In 1979, a fairly detailed study of aircraft fire accidents was performed by the NATO Advisory Group for Aerospace Research and Development (AGARD)[3.1]. The results presented in the study are based on an examination of 1964-1974 civil aircraft statistics in the U.S. and a review of detailed narrative accident reports for each of the accidents. Furthermore, a number of crosschecks are presented in this study with results obtained by the Coordinating Research Council through a review of worldwide accident records. In general, acceptable agreement between the two studies was obtained.

From the accident data, AGARD identified seven fire scenarios and ranked them in Table 3.1. Of the scenarios given in Table 3.1, only No. 1, 2, 3 and 7 are fuel-related. The most important of these scenarios (Nos. 1 to 3) will be included in our study, with the exception of the in-flight fuel tank explosion (Scenario 2A). This scenario may occur when a conventional-fuel, air-breathing tank is hit by lightning. It is impossible, however, in a properly functioning LH_2 or LCH_4 fuel tank where air is excluded. Scenario No. 7 is not crash-related and is of little practical importance. Consequently, it is not included in our study.

Thus, historical accident data support the importance of the accident scenarios selected for consideration in this program. Additional pertinent results and conclusions of the AGARD study are:

- Of all civil transport accidents and incidents,* approximately, 27% are impact-survivable accidents,
- Of impact survivable fire accidents, approximately 50% result in fuel release due to wing separation of which approximately 70% result in subsequent fatality,
- Based on FAA statistics reported by AGARD (during the 1964-1974 period) 28 U.S. transport aircraft impact survivable fire accidents occurred. Fire effects resulted in 395 (40%) of the 987 fatalities in these accidents.
- Of the 28 accidents, 14 involved wing separation and the resulting fires and explosions caused 259 fatalities. Thus, fire hazards as a result of wing separation account for approximately 65% of fire-related casualties in impact survivable aircraft.
- Fuel line and tank damage were the only fuel sources in about 40% of the fire accidents; and

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*Incident refers to an event in which a fire resulted in minor damage or injury, but no fatalities.

TABLE 3.1

RANKING OF AIRCRAFT FIRE SCENARIOS (IN DECREASING IMPORTANCE)

1. Post-Crash Massive Fuel Spill Fire

    A. Wing/partial wing separation
    B. Major fuel tank damage

2. Fuel Tank Explosion

    A. Inflight
    B. Post crash

3. Post-Crash Small Fuel Spill Fire

    A. Minor fuel tank damage
    B. Fuel line damage

4. Cabin Material Fire

    A. Inflight
    B. Post crash

5. Propulsion System Fire

    A. Non-contained titanium fire
    B. Non-contained rotor fragment fire

6. Landing Gear System Fire

    A. Maintenance
    B. Inflight

7. Fuel Tank Explosion

    A. Maintenance
    B. Refueling

- Fuel tank explosions occured in 11% of the impact survivable accidents.

The above statistics answer some of the questions raised earlier in this section. A key unanswered question is the relative susceptibility of various aircraft sections to crash impact damage. The sections of interest are the wings and the fuselage where the fuel is located in the conventional and cryogenic aircraft, respectively. In the remainder of this section, we will describe the available accident data files and our analysis of them to answer this kev question.

3.3 ACCIDENT DATA FILES

We have examined three major sources of aircraft accident data. These sources are:

3.3.1 Data Files of the Military Air Safety Centers

Data on military aviation accidents are maintained by the air safety centers. The data are, however, confined to an analysis of causes and their computer files do not provide even qualitative indications of the nature of structural damage. The only information on structure failures maintained by the air safetv center are photographs which are occasionally filed with the investigative reports. Such information would be available only by a manual review of a large volume of investigation files. Such a review is outside the scope of this program, but is recommended in future programs.

3.3.2 Airframers Data Base

This data base was developed by airplane manufacturers under NASA sponsorship in connection with a study of the risks presented by the use of carbon fiber composites in commercial aviation. The aircraft is divided into 18 components. Based on historical accident data, estimates are given for the percentage of each of these components damaged by aircraft fires. Clearly, fire-induced damages are expected to be dependent on fuel type. Rather, we are interested in crash-induced damage, prior to any fuel fire. Thus, the airframers data are not suitable for our objective.

3.3.3 NTSB Data Base

This data file contains a description of all reportable civil aviation accidents which occurred from 1964 to 1978. (Reportable accidents are defined in 49 CFR Part 830.5 as accidents involving death, serious injury or significant airplane damage as well as any incident involving flight control malfunction, incapacitation of a required crew member, turbine engine rotor failure or in flight fire or collision). It represents the most comprehensive data source available and will be utilized in this program as described below.

3.4 RELATIVE SUSCEPTIBILITY OF FUEL RELEASE FROM WING-MOUNTED AND FUSELAGE-MOUNTED TANKS

In section 2, we defined the most likely aircraft concepts and configurations for the fuels under consideration in this study. We anticipate the fuel to be located in the wings for conventional fuel aircraft and in the fuselage for cryogenic fuels aircraft. The susceptibility of these two locations to impact forces can affect the amount of fuel release and the subsequent extent of the hazard.

Determining the relative susceptibility of wings and fuselage purely from structural analysis considerations is not practical in view of the expected wide variations and uncertainties in impact conditions. Counsequently, we chose to infer the results from the data available on real accidents.

We utilized two sources of data: (1) the detailed analysis of worldwide accident data conducted by the Coordinating Research Council and reported by AGARD [4.1] and (2) our own analysis of the National Transportation Safety Board (NTSB) computerized data base. The main features of these two data sources are given in Table 3.2. Note that each source provides only a part of the answers we seek. For example, the damage to the aircraft wings with subsequent fuel release is addressed by AGARD but not by NTSB. On the other hand, the damage to the fuselage (where cryogenic fuel tanks will be mounted) is reported by NTSB but not by AGARD. Accordingly, we combined the data is these two sources to compare the relative susceptibility of placing the fuel in the wings versus in

TABLE 3.2

COMPARISON OF THE AGARD (CRC) AND NTSB DATA SOURCES

Item	AGARD (CRC)	NTSB
Source of accident data	World-wide 1964 -1974	U.S. 1964 - 1978
Fuel release data	Location and probability of fuel release are specified	Not available
Occurrence of fire	Specified for each type of fuel release	Specified for each accident
Occurrence of explosion	Given	Not available
Impact damage to aircraft structure	Not available	Specified in qualitative terms and for only a fraction of the reports
Stopping distance and speed	Not available	Given
Stopping time	Given	Not available

the fuselage. This is described in the following paragraphs.

3.4.1 Data Examined in the NTSB Data File

The NTSB data file contains a wealth of information related to accident conditions. Table 3.3 gives the NTSB descriptions for each accident that we will utilize in this study. Note that reporting is required for some of these descriptions while it is optional for others (as indicated in Table 3.3). This incompleteness in the data made our analysis quite difficult.

The data file gives a total of 65,671 accident reports. They include many accidents (e.g., light aircraft) which are not relevant to the LH_2 aircraft hazard analysis. Consequently, we have restricted our analysis to those accidents which reportedly involved takeoff or landing operations of heavy turbine-powered aircraft engaged in passenger service, cargo or ferry operations (630 accidents).

We must also focus on only impact-survivable accidents to analyze the crash fire hazards of various fuels. However, the NTSB accident file does not distinguish between impact and fire fatalities. This distinction has no significant influence on this study since only 36 of the 630 accidents (i.e., ≈ 5%) had no survivors. The inclusion of some fraction of these accidents in the data base would, therefore, result in a negligible change in the overall statistics.

Of the 630 accidents, we found 79 reporting fires and 82 reporting a description of the impact damage by aircraft section. These data are summarized in Table 3.4 for each reference. Note that all numbers are sufficiently large to provide meaningful estimates.

3.4.2 Fuel Release From Conventional-Fueled Aircraft (AGARD Data)

In 1979, a fairly detailed study of aircraft fire accidents was conducted by the NATO Advisory Group for Aerospace Research and Development (AGARD). This study reported on the results obtained by the Coordinating Research Council (CRC) on world-wide aircraft accidents over the period of 1964-1974. The CRC data give a detailed breakdown of the number of accidents involving fuel release during takeoff and landing. The data are given in Table 3.5 and indicate the mode of fuel

TABLE 3.3

DATA UTILIZED FROM NTSB TAPE

Item	Description/Unit	Reporting
Extent of overall impact damage	Destroyed-substantial-minor-none	Required
Impact damage severity (non-fire) to:		Optional
-- cockpit	Extreme-severe-moderate-minor-none	
-- forward cabin	"	
-- center cabin	"	
-- aft cabin	"	
-- occupied areas	"	
Fire	Yes/No	Required
Extent of fire damage	Destroyed-substantial-minor-none-not reported	Optional
Stopping distance	Feet	Optional
Speed at impact	MPH	Optional
Number of passengers	Person	Required
Number of fatalities	Person	Required
Aircraft weight category	Light/Heavy	Required

TABLE 3.4

DATA SETS EXAMINED IN THE NTSB FILE

Item	Number of Reports
Total reported aircraft accidents	65,671
Number of reports involving takeoff or landing of heavy fixed wing turbine aircraft	630
Number involving one or more survivors	594
Number of survivable accidents involving fire	79
Number of survivable accidents where damage is reported by aircraft section	82

TABLE 3.5

NUMBER OF ACCIDENTS INVOLVING FUEL RELEASE AND THE OCCURRENCE OF FIRE IN THESE ACCIDENTS (AGARD DATA) (1964-1974)

Cause of fuel release	Occurrence of fire	
	Yes	No
Fuel tank damage only	39	26
Fuel line damage only	7	4
Combined tank and line damage	5	4
Wing separation	48	0
Total	97*	

*AGARD gives a total number of fires (97) slightly smaller than the sum (99) of the various release modes!

release (damage to a fuel line or a fuel tank, and wing separation) and the occurrence of fire.

It is of note that all 48 accidents involving wing separation have resulted in fires. This is reasonable since the impact energy required to break a wing is several orders of magnitude larger than that required to ignite a fuel air mixture. In the accidents involving the other fuel release modes, the data in Table 3.5 indicate that ignition is likely but not certain.

It is unfortunate that AGARD did not report the total number of takeoff and landing accidents from which the data in Table 3.5 are extracted. This can be inferred, however, by assuming that the fraction of fire occurrences in takeoff and landing accidents is the same as that for the NTSB data file. From Table 3.4, this fraction is $\frac{79}{630} = 0.13$. Thus, the corresponding number of accidents in the AGARD data base is $\frac{97}{0.13} = 770$ accidents. Therefore, an estimate of the probability of wing separation, given a takeoff or landing accident is $\frac{48}{770} = 0.06$ or 6%.

3.4.3 Impact-Damage by Aircraft Section (NTSB Data)

As shown in Table 3.3 reporting the overall impact damage to the aircraft is required by NTSB, while reporting the damage to each section* of the aircraft is left to the discretion of the NTSB investigator. Consequently, only 82 of the 630 takeoff and landing accidents contain damage data by section.

These 82 accidents are not a representative sample since they consist mainly of severe accidents where reporting is expected to be more thorough. This fact is supported by the data in Table 3.6, which compares the overall aircraft damage severity with the reporting of sectional damage. Note that the probability (or fraction) of reported sectional damage decreases as the overall impact to the aircraft decreases. To extrapolate from the sample to the entire population, the number of accidents in each overall-aircraft-impact-damage category was weighted by the inverse of the corresponding probability of reporting.

*The aircraft is divided into four sections: cockpit, and forward, center and aft cabins.

TABLE 3.6

COMPARISON OF OVERALL AIRCRAFT DAMAGE SEVERITY FOR ACCIDENTS WITH AND WITHOUT REPORTS ON SECTIONAL DAMAGE (NTSB DATA)

OVERALL-AIRCRAFT IMPACT-DAMAGE CATEGORY	REPORTED SECTIONAL DAMAGE		UNREPORTED SECTIONAL DAMAGE	
	No. of Accidents	Fraction*	No. of Accidents	Fraction*
Destroyed	44	0.44	56	0.56
Substantial	30	0.12	223	0.88
Minor	7	0.03	207	0.97
None	1	0.02	61	0.98
Unknown	0	0	1	1.00
Total	82		548	

*Fraction of the total number of accidents in the same overall-aircraft-impact-damage category

When reported, the extent of damage to each section is described in a qualitative fashion as "extreme, severe, moderate, minor or none".* But these terms are not well defined by the NTSB and are thus left largely at the discretion of the accident investigators. Based on conversations with NTSB personnel, we can confidently state that a rating of "extreme" denotes extensive structural damage, i.e., a likely breach of aircraft integrity; while "minor" denotes no significant damage to the aircraft structure. The intermediate categories are less clear, however. To mitigate this difficulty, we assumed two definitions of breach of integrity corresponding to "extreme" and "extreme or severe". The second definition is conservative and places an upper bound of the probability estimate of breach of integrity.

We counted the number of accidents in the NTSB data sample which correspond to these two definitions and translated them into a probability estimate of damage given a takeoff or landing accident. The results are shown in Table 3.7 for all possible combinations of damage to the cockpit, forward, center and aft cabins. Note that not all combinations of damage have occurred so far. The results will be further discussed below.

3.4.4 Susceptibility of Impact-Damage to Fuselage-Mounted Tanks (NTSB Data)

Since LH_2 or LCH_4 would be stored in two tanks located in the forward and aft areas respectively, the following three release modes are possible:

- Release from forward tank alone,
- Release from aft tank alone,
- Simultaneous release from both tanks.

These distinctions are important because they imply different volumes of fuel spillage as well as different spill locations with respect to the passenger compartment. Also, release and ignition of fuel from one tank may impact the other tank.

The occurrence rates of these three fuel release modes can be estimated from the observed damage levels of the individual aircraft sections in Table 3.7.

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*Note that these terms are different from those used in Table 3.6 to describe overall impact damage to the aircraft.

TABLE 3.7

PROBABILITY ESTIMATES FOR STRUCTURAL DAMAGE TO VARIOUS AIRCRAFT SECTIONS (NTSB DATA)

(Given a takeoff or landing accident)

Category* No.	Cockpit	Forward Cabin	Center Cabin	Aft Cabin		DAMAGE CATEGORY Extreme	Extreme or Severe
1	D	D	D	D		0.037	0.079
2	D	D	D			0.014	0.018
3	D	D		D			
4	D		D	D			
5	D		D				
6	D	D				0.014	0.007
7	D			D			
8	D					0.007	0.007
9		D	D	D			0.013
10		D	D				0.004
11		D		D			0.017
12			D	D			0.013
13		D					
14				D			0.017
15			D				
16						0.93	0.83
					Total	1.0	1.0

*D denotes damage to the section, while a blank denotes no damage. Thus, each category No. denotes a particular distribution of damage between the sections.

In particular, since the fuel tank locations proposed for the LH_2 or LCH_4 aircraft approximately coincide with the forward and aft cabin areas of a conventional aircraft, the probability of significant damage to these areas can be used to approximate release from these tanks. The results are given in Table 3.8.

3.4.5 Comparison of the Probability of Massive Fuel Release from Fuselage-Mounted and Wing-Mounted Tanks

In the last section, we estimated the probability of breaching the fuselage in takeoff or landing accidents of heavy aircraft. This estimate is only approximate since it is based on the subjective evaluation data of the NTSB investigator; and on an extrapolation from an 82-record sample to a population of 630 records. Still, it represents the best available estimate of a potential massive fuel release from a fuselage-mounted tank. This estimate is in the neighborhood of 0.08 with an upper bound* of 0.17 (from Table 3.8).

We have also estimated (in Section 3.3.2) the probability of wing separation to be about 0.06. This number is also approximate since it is based on the combination of two separate data bases. In view of the uncertainties in our two estimates, we conclude that the probability of a massive fuel release (based on an analysis of historical data) is essentially the same for both types of fuel tanks.

3.5 CONCLUSIONS

Our review of studies of historical aircraft accidents confirmed the importance of the crash fire scenarios selected for study in this project. In addition, our review of actual accident data file suggests that the fuselage and the wing are equally vulnerable to impact forces. Thus, for the purpose of comparative crash fire hazard analysis, we can assume that for given accident conditions, the total content of a fuel tank will be released regardless of the location of the fuel tank.

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*Which is based on a more conservative definition of fuselage damage.

TABLE 3.8

ESTIMATED PROBABILITIES FOR BREACHING FUSELAGE-MOUNTED TANKS (NTSB DATA)

	Categories in Table 3.7	Probability Estimate*
Forward tan' only	2, 6, 10, 13	0.03 - 0.03
Aft tank only	4, 7, 12, 14	0 - 0.03
Both forward and aft tanks	1, 3, 9, 11	0.04 - 0.11
Either forward or aft tank	All of the above	0.08 - 0.17

*Probability given a takeoff or landing accident. The two values correspond to the two damage definitions described above.

4. CHARACTERIZATION OF FUEL RELEASE CONDITIONS

In the statement of work, NASA outlined four accident scenarios to be examined in this study:

1. A nonnormal landing or ground accident which results in fuel system insulation damage and/or fuel system damage permitting liquid hydrogen to vent, escape, leak or run out of a punctured tank or broken line.

2. A survivable "crash" landing or failed "takeoff" where damage to fuel tankage or lines results in massive release of liquid hydrogen after the aircraft has come to rest.

3. A survivable "crash" landing or failed "takeoff" where damage to fuel tankage or lines results in massive release of liquid hydrogen upon impact and during aircraft deceleration.

4. A catastrophic crash resulting in the maximum rate of energy release in the form of a conflagration and/or explosion.

In this section, we identify, based on engineering judgment, specific aircraft failure modes that can be associated with these scenarios. We can then characterize the fuel release conditions for each failure mode. This provides the range of fuel release to be expected in each scenario and for each aircraft type.

We have also assessed in a qualitative way the likelihood of each failure mode for each aircraft system. This likelihood can vary significantly and should be noted when comparing the hazard from each aircraft system.

4.1 POSTULATED FAILURE MODES/EVENTS

Based on engineering judgement, we have identified eight failure modes/events that may lead to fuel release.

1. Vibration: Stress fatigue of the tanks and lines and their connections and supports, causing fracture of the tanks and lines and loosening of their connections, with the result that fuel is

released at a rate related to the size of the opening and pressure within the containment.

2. Strained Maneuver: Overstressing of the tanks and lines and their connections and supports producing a breach in the containment similar to that caused by vibration.

3. Engine Burst: Breaching of the lines and tanks by failed engine components, such as turbine blades shed by the high rpm machinery in a radial direction.

4. Sheared Engine Pod: Broken or sheared fuel lines caused by the loss of engines, i.e., as when landing gear failure causes engines to strike the ground.

5. Failed Thermal Insulation: The LH_2 and LCH_4 fuel tanks and lines must be thermally insulated. Insulation failure causes excessive gas generation that can cause pressure failure of the tank. Insulation failure on the lines will interrupt the fuel flow to the engine.

6. Sheared Wing: Wing tank lines are breached when the wing is sheared from the fuselage by ground obstructions. The fuselage remains intact.

7. Broken Fuselage: Fuselage tanks and lines are breached by impact of the fuselage with the ground or obstruction. The wings remain intact.

8. Fragmented Aircraft: All fuel tanks and lines are breached regardless of their location in the aircraft.

These failure modes/events can all cause a line or a tank rupture leading to a fuel release as illustrated in Table 4.1. (In addition, insulation failure of a cryogenic system can lead to direct venting of gas or liquid). However, the probable number of fuel systems affected in each case and its relative likelihood are differen.. This is shown in Table 4.2, where likelihood is assessed qualitatively (based on engineering judgment) and is denoted by 0 = Nil, L = Low, M = Medium, H = High and 1 = Certain. Note that each failure mode/event may have the same effect for the LH_2 and LCH_4 methane fuel systems, but a different effect for the Jet A fuel system. This is due principally to the location of the LH_2 and LCH_4 fuel tanks within the fuselage, and to their special construction.

For example, Table 4.2 shows that an engine burst is expected not to damage the cryogenic fuel tanks but to damage the Jet A fuel tanks. Further, the Jet A fuel tanks are not thermally insulated and, therefore, cannot fail because of a failed insulation. On the other hand, a fragmented aircraft has a high probability of causing all three fuel systems to fail completely. Thus, Table 4.2 is an attempt to establish the relative susceptibility of the three types of fuel systems to the same failure modes or events.

4.2 FUEL RELEASE RATES AND QUANTITIES

When a fuel system failure occurs, the rate of release depends upon the location and size of the breach and on the fuel pressure. For example, a severed fuel line at the outboard engines has a limited release rate. On the other hand, a badly ruptured tank can dump its fuel load very quickly.

In Appendix A, we present a detailed discription of the fuel tanks for LH_2, LCH_4 and Jet fuel aircraft, including the tank size and number, booster pumps, flow rates and the line sizes and pressures. We also estimate the fuel release rates for various locations of the breaks in the piping and various penetration sizes in the fuel tank. The results are described in detail in Appendix A. The results of Appendix A are summarized in Table 4.3 for the eight failure modes/events. Note that, for a single failure mode, the fuel flow rates can vary significantly

TABLE 4.1

FAILURE MODES AND EVENTS RESULTING IN FUEL RELEASE

FAILURE MODE/EVENT	DESCRIPTION OF POSSIBLE FUEL SYSTEM FAILURE
1. Vibration	Ruptured Line Ruptured Tank Broken Line and Tank Connections
2. Strained Maneuver	Ruptured Line Ruptured Tank Broken Line and Tank Connections
3. Engine Burst Generates Turbine Blade Projectiles	Ruptured Line Ruptured Tank(s)
4. Sheared Engine Pod(s)	Ruptured Line(s)
5. Failed LH_2 and LCH_4 Tank and Line Insulation	Gas and Liquid Vented Through Relief System Loss of Engine Feed Ruptured Line(s) Ruptured Tank(s)
6. Sheared Wing(s)	Ruptured Line(s) Ruptured Tank(s)
7. Broken Fuselage	Ruptured Line(s) Ruptured Tank
8. Fragmented Aircraft	Ruptured Lines and Tanks

TABLE 4.2

FAILURE MODES/EVENTS VERSUS THE PROBABLE NUMBER OF AFFECTED FUEL SYSTEMS AND THEIR LIKELIHOOD

	Components of Fuel System Affected[1]					
	LH_2		LCH_4		Jet A	
FAILURE MODE/EVENT	Line(s)	Tank(s)	Line(s)	Tank(s)	Line(s)	Tank(s)
1. Vibration	1/M	2/M	1/M	2/M	1/L	1/L
2. Strained Maneuver	1/M	2/M	1/M	2/M	1/L	1/L
3. Engine Burst	1/L	0	1/L	0	1/L	1/H
4. Sheared Engine Pods	2/1	0	2/1	0	2/1	2/M
5. Failed Thermal Insulation[2]	1/L	2/H	1/L	2/L	0	0
6. Sheared Wing	2/1	?	2/1	?	1/H	2/H
7. Broken Fuselage	2/H	2/H	2/H	2/H	1/H	2/H[3]
8. Fragmented Aircraft	4/1	4/1	4/1	4/1	4/1	4/1

(1) Symbols in tables indicate the estimated number of fuel systems that are expected to fail due to the failure mode/event followed by their likelihood given that the event occurred: 0 = Nil, L = Low, M = Medium, H = High, and 1 = Certain.

(2) LH_2 tank insulation is a vacuum insulated glass microsphere system which is more vulnerable than the closed cell polyurethane insulation of the LCH_4 tank.

(3) Fuel tanks in fuselage

(?) Effect unknown

TABLE 4.3

FAILURE MODES/EVENTS AND THE CORRESPONDING ESTIMATES OF FUEL RELEASE RATES

PRIMARY CAUSE OF FUEL SYSTEM FAILURE	Fuel System Release Rates, lb/sec[1]					
	LH_2, 56,000 lb.		LCH_4, 152,000 lb.		Jet A, 187,000 lb.	
	Line(s)	Tank(s)	Line(s)	Tank(s)	Line(s)	(Tank(s)
1. Vibration[2,3]	1.3-4	2	4-11	8	19	5
2. Strained Maneuver[2,3]	1.3-4	2	4-11	8	19	5
3. Engine Burst[2,3]	1.3-4	0	4-11	0	19	5
4. Sheared Engine Pod(s)[4]	1.3-5	0	4-14	0	19-80	0
5. Failed Thermal Insulation	1.3-4	0-E[6]	0	0	0	0
6. Sheared Wing(s)	4-7	?	10-20	?	N	E[7]
7. Broken Fuselage	4-16	E	11-40	E	N	E[8]
8. Fragmented Aircraft	N	I	N	I	N	I

(1) Values in Table represent rate of fuel loss in lb/sec.

(2) Line rates for LH_2 and LCH_4 aircraft are for 300 and 30 feet equivalent length.

(3) Tank rates for a puncture, equivalent in area to the flow area of one fuel line.

(4) Line rates for one to four severed lines.

(5) Causes 1, 2, and 5 affect half of the aircraft fuel system. Causes 6 and 7 can affect half or all of the aircraft fuel systems. Cause 8 affects all of the aircraft fuel systems.

(6) Failure of the LH_2 insulation can cause overpressurization of the tank.

(7) Wings contain 70,000 lb fuel each.

(8) Fuselage tank contains 48,000 lb of fuel.

(?) Effect is unknown.

(E) Entire tank content is released in up to a few minutes -

(I) Instantaneous release of the entire fuel content of the plane (greater than 1000 lb/sec.).

(N) Line release has a negligible effect on the hazard, compared to tank release.

among the three aircraft systems. For example, sheared wings is likely to lead to a small release for the cryogenic aircraft; while it may lead to a massive release for Jet A aircraft. Thus, sheared wings should be associated with scenario 1 for the cryogenic aircraft, and with scenario 2 (or 3) for the Jet A aircraft. This point should be remembered in comparing the crash hazards of the two types of systems.

Finally, in Table 4.4, we associate each of the four accident scenarios with a number of failure modes and events, and show the basis for the calculation of the fuel release rate or quantity in each case. The duration of these fuel releases will be assumed continuous for small leaks and over a period of up to a few minutes for scenarios 2 and 3. These results will be used as input for the fire hazard analyses presented in the following chapters.

TABLE 4.4

SCENARIOS AND ASSOCIATED FUEL RELEASE RATES AND QUANTITIES

Crash Scenario	Fuel Release Rate	Failure Modes/Events	Assumed Fuel Rates or Quantities
1	Minor	1, 2, 3, 4, 5, 6 and 7	Fuel Released From One to Four Fuel System Through an Opening Equivalent in Flow Area to the Main Fuel Line
2	Massive Fuel Release With Aircraft at Rest	5, 6 and 7	Rapid Dump at Constant Rate of Two (2) or Four (4) Engine Fuel Systems Over a Period of up to a Few Minutes*
3	Massive Fuel Release With Aircraft in Motion	5, 6 and 7	
4	Catastrophic Crash	8	Instantaneous Dump of All on Board Fuel

*This applies to cryogenic aircraft mainly. For JAF aircraft, one to six tanks may be involved depending on the conditions.

5. QUALITATIVE DISCUSSION OF POTENTIAL HAZARDS

In this section, we consider the four generic accident scenarios delineated by NASA in our Statement of Work and discuss the physical processes occurring during the progression of events in the accident scenario. The major hazard models used in the detailed analysis and comparison are presented in Sections 6 and 7.

5.1 MINOR FUEL RELEASE

Minor Fuel tank or line damage can occur during take-off roll or landing approach due to landing gear failure or impact with obstacles as a result of insufficient directional control. Such an accident may result in the fuel leaking to the outside of the aircraft or to an internal compartment. These two cases are considered below.

5.1.1 Minor Release to the Aircraft Exterior

Consider a small liquid fuel leak from a moving aircraft. The fuel will exit as a jet and the liquid air interface will break down into droplets due to shear forces. A two-phase vapor-aerosol* jet will be formed. The conditions for the formation of aerosols, their size distribution or even the source strength (in kg/s) of fuel release may not be very easy to evaluate unless the leak flow rate is externally controlled such as by a fuel pump.

As air is entrained into this jet, the droplets will evaporate. Evaporation will depend on the volatility of the fuel, being fastest for hydrogen and slowest for Jet A. Models are available for droplet evaporation and can be readily applied once the droplet diameter is known.[5.1]

*A vapor-aerosol mixture is a two-phase mixture where the liquid phase is concentrated in the form of droplets that are too small to settle out. The droplets are entrained in the vapor phase and therefore increase the mixture density significantly.

If this jet ignites,* a flame will develop and may attach itself to the aircraft or blow away, depending on the aircraft speed and the flowfield near the region of fuel release.[5.1] Analytical models and experimental data exist for describing the characteristics of an attached jet fire given the strength of the source and the type of fuel. These characteristics include flame diameter, length and temperature distribution.[5.2]

The thermal radiation from such fires can also be calculated using available models. For example, Becker[5.3] has recently presented a methodology for calculating the radiation from natural gas flare fires. Tan[5.4] has given monographs for flare stack design taking into consideration the thermal radiative effects.

5.1.2 Internal Release

A small fuel release into an internal compartment of the aircraft may perhaps be more hazardous than a release to the external environment. The released fuel will evaporate relatively slowly in the case of Jet A and rather rapidly in the case of LCH_4 and LH_2. There are two main potential hazards from such leaks: explosions and thermal shock (when a cryogenic fuel comes in contact with an uninsulated metallic structure).

For a given fuel release into an internal compartment, it is possible to estimate with available models the evaporation rate, the mixing rate of vapors with air and, if there is ignition, the explosive yield. It will be difficult, however, to determine whether simple deflagrative burning will occur or whether detonation will ensue. While both types of combustion of vapors may pose a threat to the passengers, detonation will probably pose the greatest threat. The presently available models are not adequate to specify the exact conditions under which detonation will result. (The propensity for detonation will be enhanced by structures in the hold, additional confinement and the nature of the ignition source.)

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*Potential ignition sources include hot engine surfaces, friction sparks or hot brakes.

5.2 MASSIVE FUEL RELEASE WITH AIRCRAFT AT REST

In this accident scenario, wing separation or major fuel system damage is assumed to occur, due to impact with an obstacle late in landing roll or during the final deceleration of a comparatively minor crash. A typical scenario might be a collision with an obstacle as a result of loss of directional control subsequent to landing gear failure.

A massive fuel release is assumed after the aircraft has come to rest. The fuel will spread on the ground and boil in the case of cryogenic fuels (LH_2 and LCH_4); spread and evaporate in the case of Jet A. Also, in the case of LH_2, because of the higher than ambient tank pressure, some flashing of liquid to vapor will occur. The extent of liquid spread on the ground, and the total vapor liberation have been recently modeled.[5.5]

Should ignition occur, a turbulent diffusion-controlled pool fire will result. The height of this flame has been modeled by Thomas (for low Froude Number [5.6]; and the resulting thermal radiation field by Raj.[5.7]

The pool fire will engulf the aircraft thereby possibly threatening adjacent fuel tanks. After sufficient heating by the pool fire, these tanks can explode. Upon explosion of a fuel tank, its contents may burn in a rising fireball. Fireballs have been modeled by Fay and Lewis [5.8] and Hardee et al. [5.9]

Should ignition be delayed, the vapors generated from a cryogenic fuel pool, will disperse in the wind forming a vapor cloud. It is critical to determine whether the cloud is initially negatively buoyant and the distance it will travel before becoming positively buoyant. Once the cloud is positively buoyant, it will rise and the hazard will essentially dissipate.

At saturation, LCH_4 vapor is heavier than air and gravitational spreading effects are noticeable in larger releases. If aerosol is formed, the dispersing cloud will be even more negatively buoyant and is likely to disperse at grade.

Saturated LH_2 vapor is about the same density as air and, if heated, can become positively buoyant. Again, if aerosol is formed, the dispersing cloud may be negatively buoyant. This is also true of a dispersing aerosol cloud of JAF.

In one large scale spill test of liquid hydrogen, conducted by ADL in 1960, a long (fog) cloud was seen to disperse at ground level and no plume rise was observed. This issue is being further investigated by NASA (Langley). In addition, a number of experimental research programs are presently under way to generate a better understanding of the dispersion behavior of various heavier-than-air-vapors. These programs include: (i) the liquefied natural gas (LNG) dispersion tests at the Naval Weapons Center, China Lake, California, for the U.S. Department of Energy; (ii) the ammonia spill tests at the above location for the Fertilizer Institute and the U.S. Coast Guard; (iii) the Porton Down tests in England involving the instantaneous release of Freon; (iv) the (proposed) heavy gas dispersion trials on behalf of the Health and Safety Executive of the British Government and other participants; and (v) the LNG spill tests conducted by Shell UK Ltd. on Maplin Sands, England. These tests are all in various phases of development. In many cases, the data are unavailable or they have not been analyzed as yet.

There are several models in the literature describing the dispersion behavior of heavier-than-air gases under a wide range of conditions. Models which discuss the dispersion of vapors released passively (as from a boiling pool of liquid) include Germeles and Drake,[5.10] Van Ulden,[5.11] Britter,[5.12] and Colenbrander.[5.13] Recently, a model has been developed for the dispersion of heavy gases containing unstable aerosols released from stacks of various heights.[5.14] There are also models in the air pollution literature dealing with release of neutral and positively buoyant vapors from stacks.

In general, the dispersion of vapors in the far-field (after sufficient dilution) can be predicted with reasonable accuracy by the standard Gaussian models of Pasquill[5.15] and Gifford.[5.16] However,

in the near-field, these models have to be modified to take into account the effects of initial gravitational spreading, jet mixing or the effects of aerosol evaporation.

Should the dispersing flammable plume encounter an ignition source a vapor cloud fire will occur. Recent large scale experiments on the ignition of liquefied natural gas and propane vapor clouds produced a highly turbulent deflagrative burning.(5.17) Other field experiments have also indicated similar behavior in which the flame speed is in the 10 m/s to 20 m/s range.(5.18) However, small scale laboratory tests conducted with obstructions in the path of an advancing fire indicate significant flame accelerations up to about 100 m/s.(5.19) In the latter case, significant overpressures may result with the potential of blast-induced damage to the surroundings.

5.3 MASSIVE RELEASE WITH AIRCRAFT IN MOTION

This accident scenario may occur due to aircraft overshooting an approach or colliding with obstacles during take-off. Its importance was noted in the AGARD study, while fuel release with the aircraft at rest was not noted by AGARD. They can both be thought of as occurring during the same accident, however, since part of the fuel may be released while the aircraft is in motion and the rest after the aircraft stops.

Accident data show that collision may cause the separation of one wing, both wings, or structural damage of one wing followed by separation of the other wing. Air shear results in the formation of a mist of fuel droplets which are readily ignited and which provide an ignition source for subsequently released fuel. The period between initial fuel release and aircraft coming to rest may be up to 10 seconds. Ignition sources include hot engine surfaces, internal engine fire, severed electrical wiring, friction sparks, or hot brakes.

To our knowledge, this fire scenario has not been modeled as yet. However, its modeling appears feasible based on current knowledge. The fire produced can be thought of as a combination of the two types of fires described in the previous two scenarios. Part of the released fuel will burn as a spray (like in Scenario No. 1), while the rest will

fall on the ground as a liquid stream and will burn somewhat like a pool fire (Scenario No. 2).

The geometry of the liquid stream will be determined by the fuel release rate, the aircraft motion, the liquid spread rate due to gravitational forces, and its rate of consumption in the fire. As the liquid spreads, it will evaporate due to heat transfer from the fire and from the warmer ground (for cryogenic fuels only). The vapors will mix with air and burn a turbulent diffusion-controlled flame.

The relative sizes of the spray and stream fires will depend on the rate of fuel release and the aircraft speed. The spray fire is expected to impact the aircraft, while the stream fire will impact the crash site. Accordingly, the relative importance of these two fires will depend greatly on local conditions.

5.4 CATASTROPHIC CRASH

The final scenario considers a very severe crash resulting in an instantaneous release of all the fuel tanks' contents. Such a release is possible if the aircraft impacts, for example, a mountain or falls to the ground because of complete loss of power. In such cases, the hazard to the passengers may be more from the mechanical impact rather than from the subsequent fire. Therefore, the concern in the above release scenario is for people and structures in the area surrounding the crash site.

When an aircraft rams into a mountain or the ground, the impact energy causes the aircraft structures to deform. The fuel tanks may be compressed in such an accident, resulting in the rapid squirting of all of the fuel into the atmosphere, essentially in the form of a fine spray. Clearly, hydraulic ramming also contributes to the formation of this spray.

The impact energy also provides the ignition source for the spray. The spray burns in a fireball whose size and rate of rise can be calculated using existing fireball models.[5.7, 5.8]

In this scenario, the energy release rate may be sufficiently high to produce a blast wave with damaging overpressures at distances away from the crash site. The blast wave characteristics can best be modeled by a TNT-equivalent approach.[5.20] This approach is particularly successful in predicting far-field effects which is the region of most interest to bound the extent of the damage area.

Over the years, TNT yield factors have been estimated for accidental explosions. This is done by estimating the amount of fuel released and the strength of the blast from the observed damage. Clearly such estimates are subject to large uncertainties. Still, they provide the best indication of what happens in real life.

Table 5.1 summarizes probably the most complete listing [5.21] of major, well-documented incidents involving vapor cloud explosions that has been compiled to date. Each line entry in Table 5.1 includes estimates of the amount of flammable gas or liquid released, the TNT equivalent charge, and the yield factor. Note that the yield factor is below one percent for half of the incidents and below 10 percent for 17 of the 22 incidents. Still the entire range of yields is 0.06 to 65 percent covering three orders of magnitude. Much of this variability may be due to the volume of fuel in the vapor cloud which actually is in the flammable range.

In addition, we present in Table 5.2 a second compilation of TNT yield factors reported in the literature. Section A of Table 5.2 provides general recommended values based on reviews of research tests, theories and the accidental data presented in Table 5.1. Section B provides the data reported for hydrogen only. Note that the range of yield data is also very broad.

Based on Table 5.1 and 5.2, it is evident that the yield can vary significantly depending on the specific conditions of the release and the explosion. Furthermore, the available data is not sufficient to differentiate with confidence between the four fuels of interest to this program.

TABLE 5.1

TNT YIELD DATA FOR UNCONFINED VAPOR CLOUD EXPLOSIONS(5.21)

FUEL	QUANTITY (kg)	STATE* RELEASED	TNT EQUIVALENT (kg)	YIELD (%)	COMMENTS
Hydrogen	6,900	G	430	0.25**	Involved a dirigible.
Hydrogen	90	G	27	1**	Venting experiment, no confinement.***
Hydrogen	300	G	10-20	0.1-0.2**	Storage vessel involved
Hydrogen and CO	70-140	G	12	1**	Valve failure.
Cyclohexane	3,860	SL	25	0.06	Valve failure on process reactor.
Ethylene oxide	22,000	SL	18,200	18	Tank rupture.
Ethylene	90-230	G or SL	120-300	13	Pipe fitting failure. Partial confinement.
Ethyl Chloride	17,360	SL(?)	150-200	0.25	Line rupture on process reactor.
Methane	500	CL	1,000-2,000	19-36	High yield disputed.
Isobutylene	9,100	SL	10,000-12,000	11-13	Valve failure.
$\leq C_9$ HC's	50,000-100,000	G	20,000	4-8	Involved slop oil tank.
$>C_{10}$ HC's and H_2	114,000	SL	50,000	4	Process reactor failure.
Propane	70,000	SL	50,000	7.5	Pipeline rupture.
Ethylene	3,640	G or SL	500	1	Frozen relief valve.
Propylene	54,000	SL	1,000-2,500	0.2-0.5	Tank car collision
Cyclohexane	36,000	SL	18,000	5	Pipe failure.
Propane	63,000	SL	20,000-40,000	32-65	Rail car accident.
Butadiene	<80,000	SL	20,000-57,000	3-7	Rail car puncture.
Pentanes	7,600	SL(?)	1,300	2	Pipe Failure.
Propylene	5,450	CL	2,200	4	Cold liquid to flare header.
Isobutane	68,200	SL	1,600	0.25	Tank car puncture.
Ethylene	900-2,700	G or SL	7+	0.02+	Pipe leak.

*"G": gas
"SL": superheated liquid
"CL": cryogenic liquid

**Note that all incidents primarily involving hydrogen have a yield in the range of 0.1 to 1.0% according to published accounts.

***Gugan believes the correct yield for this hydrogen incident is roughly 8%

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TABLE 5.2

SUMMARY OF TNT--YIELDS REPORTED IN THE LITERATURE FOR FUEL-AIR EXPLOSIONS

Source	TNT-Yield (%)	Comments
A. YIELDS RECOMMENDED IN REVIEW ARTICLES		
Lees[5.22]	1 - 10	Based on review of accident data.
Bureau of Mines[5.23]	1 50	For gaseous plumes For gaseous puffs Based on dispersion calculations of the flammable portion of the released material
Eichler and Napadensky[5.24]	20.6 28.5	For hydrocarbon/air mixture. For hydrocarbon/oxygen mixture. The above two values were obtained by fitting Kogarko's[5.13] test data. They also computed theoretically the fraction of the lower heat of combustion that is available as hydrodynamic energy in the blastwave. This fraction agreed with the yield for the case of HC/O_2 but not for HC/air.
Nuclear Regulatory Commission[5.24]	10	
West German Reactor Safety Commission[5.24]	50 100 100	For liquefied gases under pressure. For liquefied gases with triple bond for gases.
B. YIELDS REPORTED FOR HYDROGEN		
Arthur D. Little, Inc.[5.25]	56	20 lb of TNT/lb of H_2
Bulkley and Jacobs[5.26]	28	10 lb of TNT/lb of H_2
Bradford[5.27]	0.84	0.3 lb of TNT/lb of H_2
Hord[5.28]	68	28 lb of TNT/lb of H_2, based on the Helmholtz free energy.
Mt. Auburn Report[5.29]	0.1 1.0 45.0	"For small mixing". Extended plume and good mixing. Instantaneous puff and good mixing.

Note: Numbers in parentheses () refer to Reference Numbers.

The yield factor can be though of as the product of two fractions η_1 and η_2:

where

η_1 = the fraction of the total fuel release that is within the flammable range. This fraction depends on the fuel properties and the release conditions which affect the evaporation and mixing of the fuel and air; and on the width of the flammable range; and

η_2 = the fraction of the lower heat of combustion (of the fuel in the flammable range) that is transmitted to the blast.

Since η_1 can vary depending on the release and combustion conditions, a whole range of yield factors is expected for the same fuel. This explains the large variations observed in Tables 5.1 and 5.2.

The greatest variability from scenario to scenario is expected in the value of η_1, which is highly dependent on the release conditions. However, values for η_2, the fraction of the heat of combustion that is available as blast energy, can be estimated on a comparative basis for the fuels of interest if we assume that an ideal Chapman-Jouquet detonation occurs.

Thus, following Eichler and Napadensky,(5.24) the available hydrodynamic energy per unit mass of mixture can be computed as:

$$E_H = W + E_{KE} - E_D \qquad (5.1)$$

where

$$W = \int_{v_{cj}}^{v_f} P dv = \text{Expansion energy} \qquad (5.2)$$

$$E_{KE} = 1/2\ u_{cj}^2 = \text{Kinetic energy} \qquad (5.3)$$

$$E_D = 1/2\,(P_{cj} + P_o)\,(v_o - v_{cj}) = \text{Detonation compression energy} \quad (5.4)$$

where

P = Pressure

v = Specific volume

u = Gas velocity

and the subscript o and cj denote the initial Chapman-Jouguet detonation conditions, respectively.

This formulation is useful because it does not depend on empirical data such as final cloud size and can be readily computed since the detonation state does not vary as it propagates. Assuming perfect gas behavior of the explosion products with constant specific heat ratio (γ), and an isentropic expansion, we have:

$$P = P_{cj}(v_{cj}/v)^{\gamma} \quad (5.5)$$

and, therefore,

$$W = \frac{P_{cj}v_{cj}}{\gamma - 1}\left[1 - \left(\frac{P_o}{P_{cj}}\right)^{(\gamma-1)/\gamma}\right] \quad (5.6)$$

The results are presented in Table 5.3 for mixtures of hydrogen/air, methane/air and gasoline/air covering the detonable range for each fuel. Note that for each fuel E_H can vary substantially (up to 80 percent for H_2) depending on the fuel concentration in the cloud. Furthermore, E_H varies from fuel to fuel. On the other hand, η_2 varies little between the three fuels and over their detonable range (maximum variation = 15 percent).

TABLE 5.3

AVAILABLE HYDRODYNAMIC ENERGY AS A FRACTION OF THE LOWER HEAT OF COMBUSTION

Mole Concentration of Fuel in Mixture %	Equivalence Ratio ϕ	Lower Heat of Combustion, ΔH_{LC} Kcal/kg*	Available Hydrodynamic Energy, E_H Kcal/kg*	$\eta_2 = \frac{E_H}{\Delta H_{LC}}$
Hydrogen/Air				
18.3	0.54	440	270	61
24.0	0.75	620	370	61
29.5	1.00	810	470	58
44.0	1.87	790	490	62
59.0	3.4	760	480	63
Methane/Air				
6.3	0.64	430	270	63
7.9	0.82	540	340	63
9.5	1.00	660	400	61
11.5	1.24	640	390	61
13.5	1.49	640	350	56
Gasoline/Air				
1.2	0.70	470	300	65
1.7	1.0	660	410	61
3.5	2.1	620	310	50

*kg. of mixture

In addition, our numerical results show that the terms E_{KE} and E_D are each approximately equal to 20% of E_H and their contributions to Equation (5.1) cancel out. Thus, the available hydrodynamic energy (E_H) is approximately equal to the isentropic work of expansion. This finding is consistent with the results of an independent theoretical analysis of the blast wave from a pressurized sphere by Strehlow.[5.30]

Because of the weak variation in η_2, the above analysis does not essentially differentiate between the blast hazard associated with the three fuels. Still, it provides an upper bound on the values of the yield factor for well mixed vapor clouds. This upper bound (near 65 percent of the lower heat of combustion) is needed to calculate a conservative upper bound on the blast. It is interesting to note that the highest volume for η_2 in Table 5.3 is the same as the highest yield reported by Gugan for a propane accident (in Table 5.1), namely 65%.

5.5 HAZARD SCENARIOS FOR COMPARATIVE ANALYSIS

In the preceding paragraphs, we described the physical processes that might take place after a fuel release. Clearly, some of these processes are mutually exclusive. For example, ignition upon impact will preempt the dispersion of a vapor cloud.

Under crash accident conditions involving large fuel releases, we believe that ignition is very likely. This is due to the presence of a number of potential ignition sources such as the engine and its hot surfaces, the hot brakes, the sparks and hot surfaces produced by friction during impact and the possible exposure and shorting of electrical cables.

Thus, we do not believe a comparison between fuels with respect to vapor dispersion and subsequent delayed ignition is necessary. While delayed ignition is a possibility for smaller fuel releases, downwind dispersion hazard zones for such spills are not very great. Furthermore, there is much uncertainty at present in available dispersion models for LCH_4 spills and even more uncertainty in models for

LH_2 vapor dispersion. Thus, comparisons will be unreliable in any case until more experimental spill tests are conducted to allow improvement or verification of existing models.

The uncertainty in predicting dispersion behavior carries over to the problem of predicting potential blast effects in unconfined or partially confined fuel vapor clouds. The amount of fuel in the flammable range in a particular accident scenario is highly dependent on the release conditions and post-release dispersion. The variability in these factors are so great that they would over-ride fuel-specific factors.

Thus, the remaining significant scenarios where comparisons among LH_2, LCH_4 and JAF can be made, involve pool fires (from either continuous or instantaneous releases of fuel) and fireballs which are associated with catastrophic crashes. The next two sections address these effects in more detail.

6. FIREBALL HAZARDS

Under the catastrophic crash scenario (No. 4), we consider a very severe accident such as mid-air collision or an aircraft impacting a mountain or falling precipitously to ground (due to loss of power). Under these conditions, the impact energy causes the aircraft structure to deform. The fuel tanks may be compressed, resulting in the rapid squirting of all of the fuel into the atmosphere, essentially in the form of a fine spray. Clearly, hydraulic ramming also contributes to the formation of this spray. The impact energy also provides the ignition source for the spray. The spray burns in a fireball that expands as it rises in the sky.

In this section, we quantify the thermal hazards from such fireballs to people in the vicinity, of the accident location such as bystanders, or emergency crew. (The passengers can be assumed not to survive such a catastrophic crash). First, we present a simple model to determine the fireball size, duration and rise above ground. Secondly, we review the pertinent thermal radiation data reported in the literature and develop radiation models for LH_2, LCH_4 and jet fuel fires. Final, we estimate the radiation hazard zone surrounding a fireball for a range of fuel release volumes.

6.1 FIREBALL MODEL

Fireballs have been studied experimentally by a number of investigators.[Refs. 6.1 to 6.4] They released various types and amounts of fuel, ignited it and measured the fireball diameter and duration. Their results have all yielded relationships of the following form:

$$\text{Diameter} = C_1\ (\text{Mass})^n \tag{6.1}$$

$$\text{Fire Duration} = C_2\ (\text{Mass})^m \tag{6.2}$$

Where $n \approx 1/3$

$m \approx 1/6$ to $1/3$

and the C's are constants.

Of these references, only Fay [6.3] presented a theoretical analysis that can be used to examine the effects of the thermodynamic and combustion properties of the fuels under consideration. His model will be briefly summarized below and applied to the conditions of this study.

Fay assumed that the fireball behaves as an unsteady, self-similar, turbulent, diffusion flame. Buoyancy forces induce mixing of ambient air with the released fuel, promoting combustion which ultimately consumes the initial fuel charge (See Figure 6.1)

Using the equations of conservation of mass and momemtum, a simple entrainment model and the assumption of ideal gas, he determined the gross flame characteristics within two empirical constraints: β = entrainment coefficient ($\simeq 0.3$) and Φ = equivalence ratio. According to his model: The maximum height of the fireball is:

$$z = \frac{1}{\beta}\left(\frac{3V}{4\pi}\right)^{1/3} \tag{6.3}$$

The maximum fire diameter is:

$$D = 2\beta z \tag{6.4}$$

The fire duration is:

$$t = \left(\frac{14\ \rho p}{g\beta\ (\rho_a - \rho_p)}\right)^{1/2}\left(\frac{3V}{4\pi}\right)^{1/6} \tag{6.5}$$

and the final fireball volume is:

$$V = \left(\frac{m\phi + 4.76\ (4n + m)}{4\phi}\right)\ \frac{T_p}{T_r}\ V_f \tag{6.6}$$

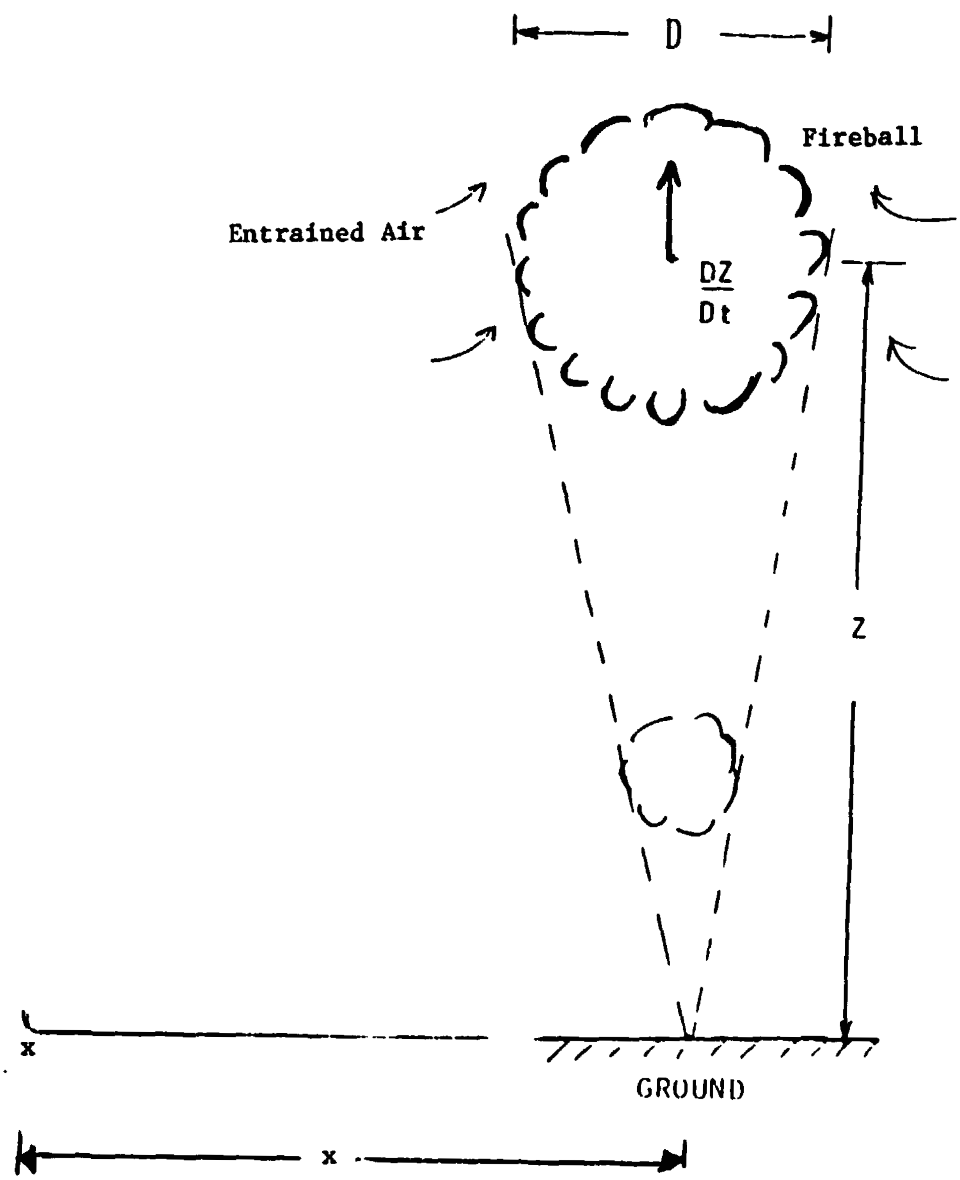


FIGURE 6.1: FIREBALL MODEL

Where ρ = density

g = acceleration of gravity

n,m = numbers of atoms in a $C_n H_m$ hydrocarbon

T = temperature

and the subscripts a, p, r, f denote air, products of combustion, reactants and gaseous fuel, respectively.

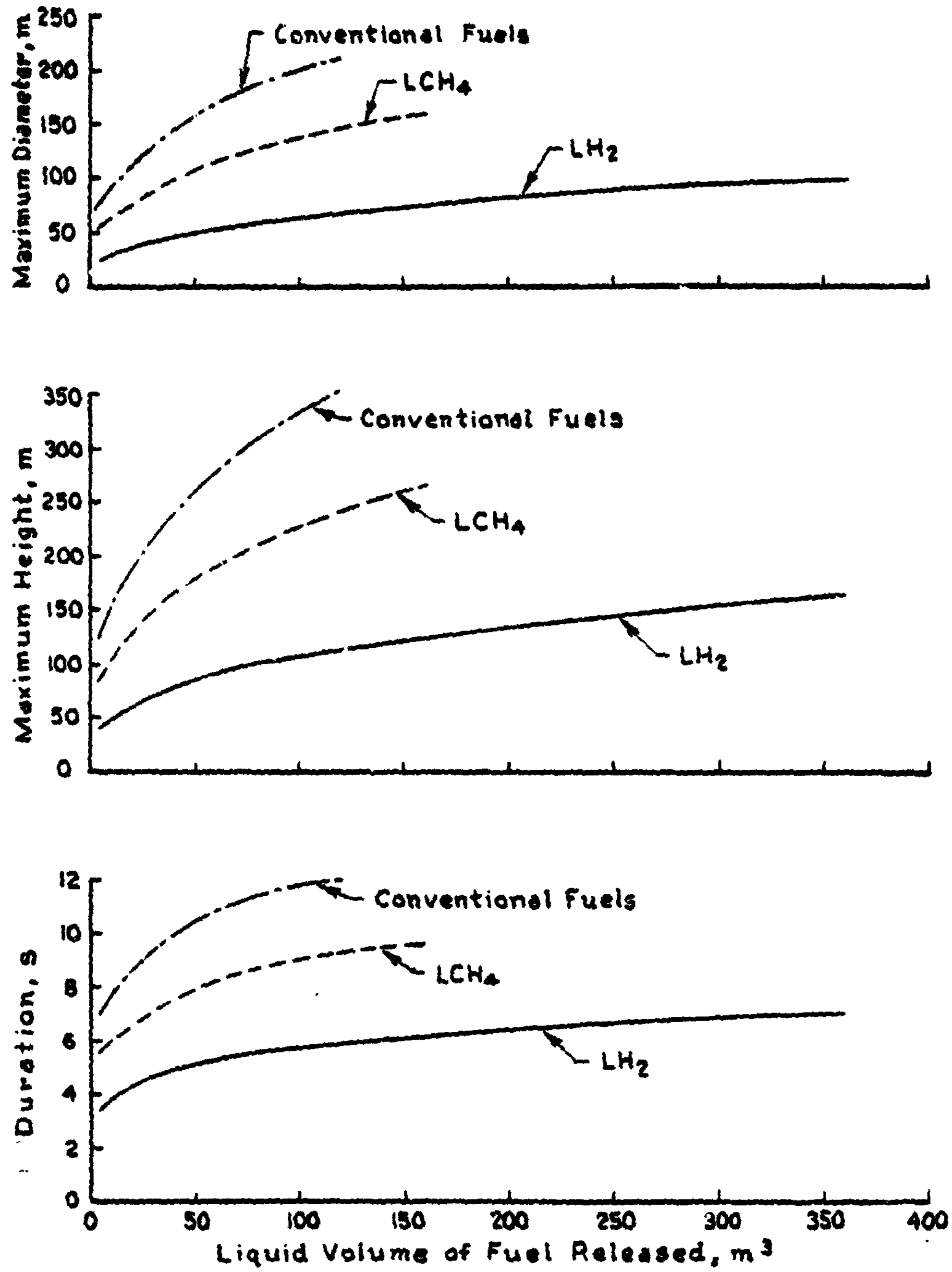
It is noteworthy that this model predicts the functional relationships determined experimentally (Eqs. (6.1) and (6.2).) Assuming a stoichometric mixture ($\phi = 1$), we applied this model to LH_2, LCH_4 and conventional* fuel releases. The results are shown parametrically in Figure 6.2 for a range of liquid volume releases (V_ℓ) corresponding to various fuel loadings in the aircraft at the time of the accident. Note that as V_ℓ increases: D, Z and t all increase which is reasonable. Furthermore, LH_2 fireballs are smaller, of shorter duration and lower rise height than those of hydrocarbon fuels. This result can be attributed to the need for a smaller volume of entrained combustion a for LH_2, than for hydrocarbon fuels of equivalent chemical energy.

6.' THERMAL RADIATION MODELS

Little thermal radiation data have been obtained directly for fireballs [6.1 - 6.4] However, numerous data have been obtained for steady, turbulent, buoyancy-driven diffusion flames over pool fires. Since a fireball can be considered the unsteady analogue of a pool fire, we can assume that the radiation characteristics of the two flames are similar.

A comprehensive compilation of the radiation characteristics of turbulent diffusion flames for large scale fires are given in Table 6.1. For each source we give a brief description of the experiment, the fire diameter, the fuel used, the radiation temperature, the emissive power (E), the fraction of the lower heat of combustion that is radiated (η), the extinction coefficient (κ) and our comments on the work. The ranges of the values reported in Table 6.1 are summarized in Table 6.2, which also gives the values used in our calculations.

*The model is too crude to distinguish between gasoline and kerosene.



COMPARISON OF FIREBALL CHARACTERISTICS
FOR VARIOUS AIRCRAFT FUELS

FIGURE 6.2

TABLE 6.1

SUMMARY OF THERMAL RADIATION DATA FOR TURBULENT DIFFUSION FLAMES

Source	Description of Work	Fire Base Equivalent Diameter, D,m	Fuel	Radiation Temperature T,°K	Emissive Power E, $\frac{kW}{m^2}$	Radiated Fraction of the lower heat of combustion η, %	Extinction Coefficient κ, m^{-1}	Comments
Rasbash (6.6)	Pan Fires with T measurements by Schmidt method and by means of a disappearing optical pyrometer with red and green filters (0.645µ and 0.525µ)	0.3	Gasoline Kerosene	1300 1250			2.0 2.6	Temperatures are based on Schmidt method which represent average flame T. Other temperatures varied by 17%.
ADL (6.7)	Instantaneous (32-500gal) and continuous (10-110gpm) spills. Total radiation measured with a thermopile.		LH_2		75-144			Uncertainty on whether flame was always in radiometer field of view.
Fishburne & Pargament (6.8)	Spectral radiation measurements and theoretical analysis of jet diffusion flames (up to 110m long)		GH_2	2200*		8.6 - 15.3		Agreement is obtained for flame radiation and height, but not width. η decreases with jet velocity.
ADL (6.9)	Unconfined spills of 3 to $5.5m^3$ on water. Spectral and total radiation measurements for pool and vapor fires.	5-50	LCH_4	1500	220±50	12.1 - 27.1		Developed band model for emission from H_2O, CO_2 and soot. Total radiation for vapor and pool fires is about the same.
May and McQueen (6.10)	Continuous spills in an irregularly-shaped trench at 0.025 to $0.074m^3/s$.	14.6-24	LCH_4			19.2		They gave η=16.4, based on the higher heat of combustion.
AGA (6.11)	Spills of up to $50m^3$ in diked areas. Spectral and total radiation measurements for pool fires.	1.8-24	LCH_4		100	19.9 - 25.3	0.49	Emissivity=1-exp(-0.49D)
Bureau of Mines (6.1-6.12)	Laboratory & field tests on pool fires and fireballs.	0.005-0.4	CH_4, LH_2, GCH_4, LCH_4 gasoline	1990*		9.5 - 30 10.3 - 23.2 30.0 - 40	4.9-7 3	First investigations to note large η for H_2. Also η increases as d increases. Different values were reported for κ in Ref. 6.1 and 6.12.
Hord (6.13)	Comprehensive review of data in literature.		LH_2 LCH_4 gasoline	2318** 2148** 2470**		17 - 25 23 - 33		
Raj (6.14)	Field tests in dikes.	7.6-15.2	JP-4	1400-1500				Due to the outer annulus of cold soot, the commended effective radiation T is 1100°K.
NWC (6.15)	Large field tests		gasoline		110			
Gruner (6.16)	Detailed study of flames over a wide range of conditions	0.1	GH_2	1700-2260				2260°K is observed only occasionally. 1700°K is corroborated by calculations based on measured composition and is recommended as most representative.
Hottel (6.17)	Review of a very comprehensive experimental study of liquid fuel pool fires.	0.0037-22.9	gasoline kerosene	1100 1100			~3 ~1	Burning rate was constant for d≥1m, suggesting an optically thick flame. T and κ were inferred.
Mc. Auburn (6.18)	Review of the literature and analytical study		LH_2			30		Used model proposed by Ref.6.12.
Sandia (6.19)	Measured the surface heat flame of a (1.5 kg pure methane) fireball	1.07	GCH_4		123			Extrapolation to an optically thick fireball yields E = 469 kW/m^2.

* Adiabatic Premixed Flame Temperatures

** Inferred, not measured.

TABLE 6.2

INPUT DATA FOR FLAME RADIATION CALCULATIONS

Item	LH_2	LCH_4	Gasoline/JP-4	Kerosene/Jet A
VALUES REPORTED IN LITERATURE				
Temperature, °K { range	1700-27[illegible] (6.16)	1500 (6.9)	950-1500 (6.17)	1480 (6.14,17)
Temperature, °K { rec**value	1700	1500	1100	1100
Emissive Power, $\frac{kW}{m^2}$ { range	75-144	100-220 (6.9)	113 (6.9)	
Emissive Power, $\frac{kW}{m^2}$ { rec. value		220	113	
Range of Radiated fraction*,%	8.5 - 25	10.3 - 33	30-40	
Extinction Coefficient,m^{-1}	4.9 - 7	0.49 - 3	2-3	2-3
CHARACTER OF EMITTED RADIATION	Band radiation from water vapor only	Band radiation from water vapor and carbon dioxide plus soot radiation	Black body radiation from soot	
MODEL/DATA UTILIZED	Band radiation from water vapor at partial pressure = 0.25 atm. and at T = 1700°K f	Grey flame with extinction coefficient = $0.49 m^{-1}$ and emissive power = 220 kW/m^2 (From Refs. 6.11, 6.9 respectively)	Black body radiation with emissive power = 110 $\frac{kW}{m^2}$ (6.9) (Equivalent to ~1200°K)	

*% of the lower heat of combustion.

**Recommended.

f See Appendix B.

As noted in Table 6.2, the character of the emitted radiation is different for the four fuels. It is mainly black body radiation for gasoline and kerosene, emission in the H_2O band for LH_2 and emission by H_2O, CO_2 and soot for LCH_4. Accordingly, we used a black body model for gasoline/kerosene and an H_2O band model for LH_2, respectively. We computed the emissivity of the H_2 flame using Hottel's mean beam length method and emissivity charts (6.5).

The development of a 2-band and soot model for the CH_4 flame was not warranted due to lack of spectral emission data and of an acceptable model for predicting soot concentrations. Accordingly, we assumed the flame to be grey as suggested by the results of the large scale AGA test (6.11).

We also used their measured value of the extinction coefficient. We believe this analysis to be adequate for the purpose of our comparative analysis of LH_2 with other fuels. The development of a more complex radiation model for a CH_4 flame is recommended for future work.

The maximum flux ($\dot{q}''(x)$) at any point (x) at grade is computed from:

$$\dot{q}''(x) = \epsilon E F \tau \tag{6.7}$$

Where ϵ = flame emissivity

F = view factor between point x and the fireball

$= \frac{D^2}{x^2 + Z^2}$, (See Figure 6.1)

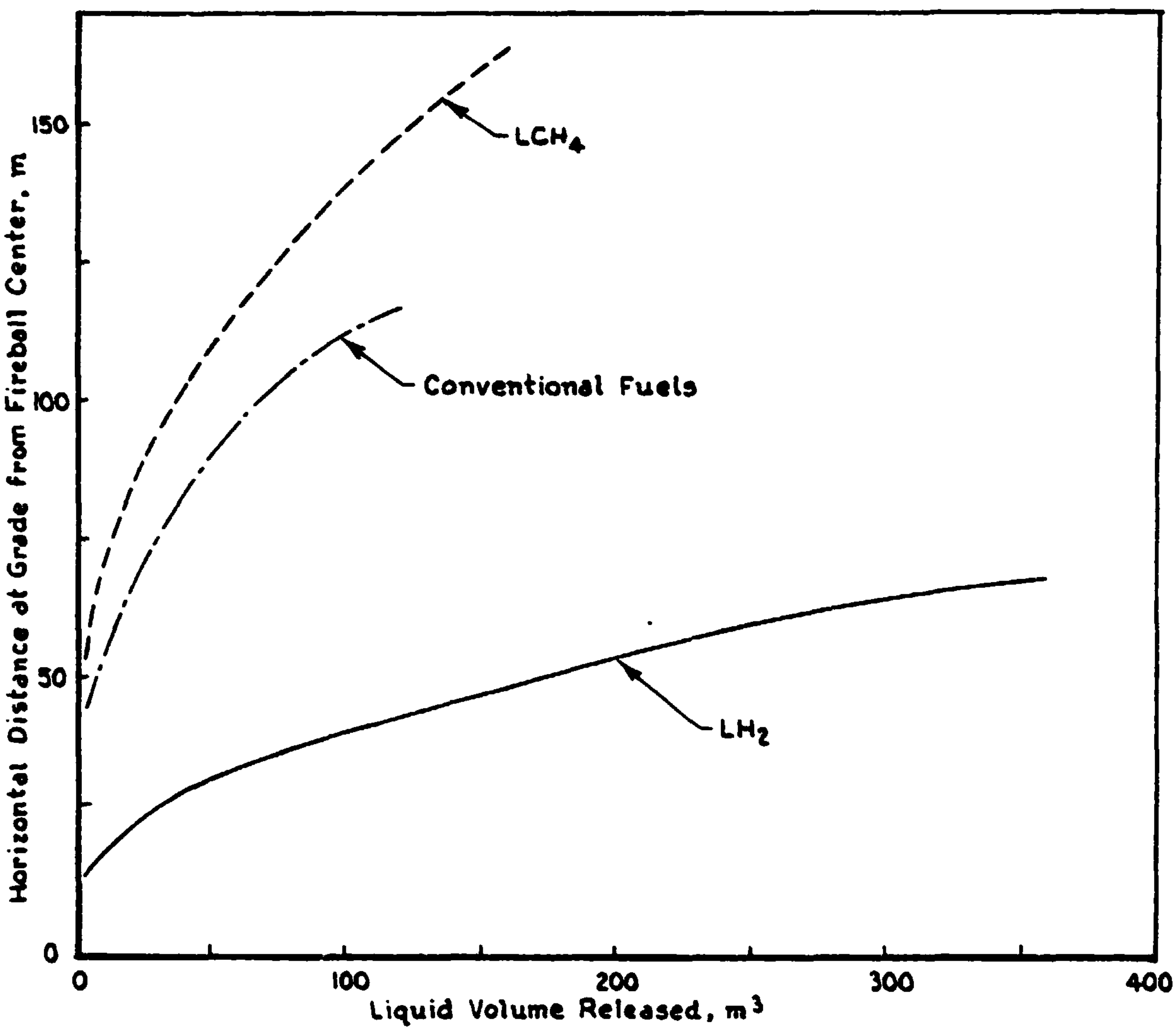
and τ = atmospheric transmissivity in the wavelengths emitted by the flame.

It has been noted that for large heavy hydrocarbon (such as gasoline or kerosene) pool fires, an outer layer of cold soot is produced. This may attenuate the radiation emitted by the hotter inner regions of the fire. We believe that the duration of fireballs is too short ($\sim$ up to 12s) to permit the formation of such a layer. Accordingly, it is not considered in the analysis.

6.3 HAZARD ZONE AROUND FIREBALLS

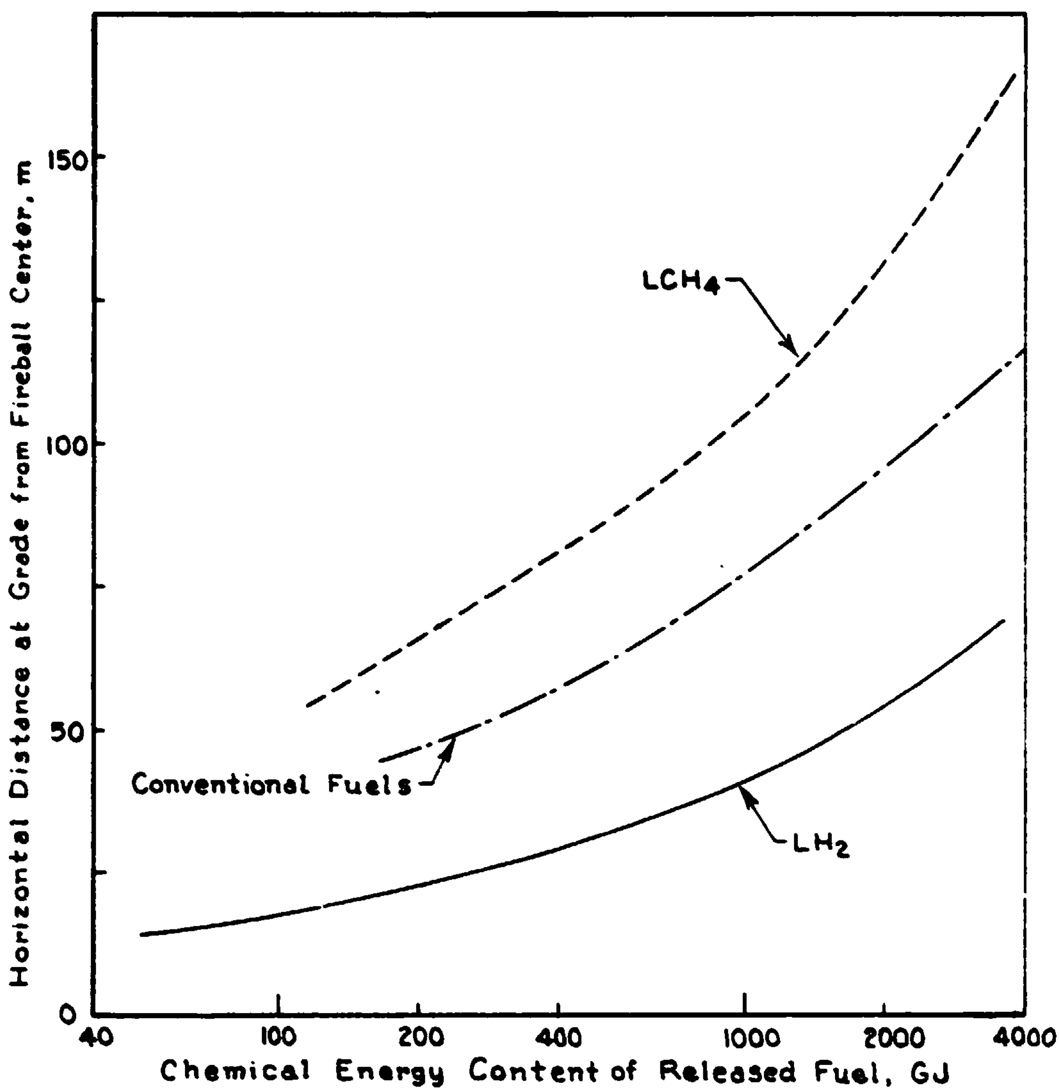
Using the fireball characteristics determined in Section 6.1 and the thermal radiation model/data of Section 6.2, we estimated the radiation field surrounding fireballs (assuming 50% ambient relative humidity) of different fuels and release volumes. Using a flux of 5 kw/m^2 as the minimum required for thermal injury of skin* over the short durations of fireballs, we made a conservative estimate of the distance at grade where this flux may be exceeded. The results are given in Figures 6.3 and 6.4 as a function of the volume and energy content of the released fuel, respectively. Note that the hazard distance is least for LH_2 and most for LCH_4.

*This value is specified in the LNG federal code (DOT-193).



COMPARISON OF FIREBALL RADIATION HAZARD DISTANCE (5Kw/m²) AS A FUNCTION OF RELEASED VOLUME

FIGURE 6.3



COMPARISON OF FIREBALL RADIATION HAZARD DISTANCE (5Kw/m²) AS A FUNCTION OF THE CHEMICAL ENERGY CONTENT OF THE RELEASED FUEL

FIGURE 6.4

7. POOL FIRE HAZARDS

7.1 INTRODUCTION

As discussed in Section 5, pool fires are the most likely hazard of concern under aircraft crash conditions. They can result in three of the accident scenarios defined in Sections 4 (no. 1, 2 and 3). For scenario 1 (a small leak), a small, quasi-steady, circular pool fire will be produced and will burn as long as the release continues. For scenario 2 (a massive leak with aircraft at rest), a transient, expanding circular pool fire will be produced and will burn until the released fuel is consumed. For scenario 3, (a massive release with aircraft decelerating) the shape of the produced pool fire will depend on the aircraft speed and path before stopping.

In all cases, the hazard of concern is the engulfment of the aircraft by the pool fire and the associated thermal radiation to the aircraft skin. (For the fire sizes of interest, thermal radiation is much more important than convection or conduction). Scenario 3 is of least concern since the aircraft moves away from the burning fuel, unless a significant portion of the fuel is released after the aircraft has reached a complete stop. In the later case, scenario 3 is reduced to scenario 2 or 1.

In this section, we will discuss the case of instantaneous release and continuous release pool fires. The models utilized in the analyses are fairly complex and vary from fuel to fuel. Accordingly, we present them separately in Appendix C and limit this section to a concise discussion of the results.

For each fuel and type of release, we characterize the fire size and duration, the flame emissivity and the heat flux or heat dose to the aircraft skin. Such a characterization is sufficient for the comparative crash fire hazard analysis intended in this project. It can also be used to determine the thermal response of the aircraft structure when sufficient information on the aircraft geometry and construction materials become available. This is recommended for future work to determine the absolute level of hazard associated with each fuel.

7.2 INSTANTANEOUS RELEASE POOL FIRES (SCENARIO 2 OR 3)

In this section, we assume that various amounts of fuel are released depending on the number of ruptured tanks and on their fuel loading at the time of the accident. The release is assumed to be instantaneous (i.e., in a few seconds). Slower release are discussed in Section 7.2.

Using the models and data on pool fires discussed in Appendix C and the LH_2 radiation model presented in Section 6.2, we calculated the main characteristics of pool fires of interest. These characteristics are given in Figures 7.1 and 7.2 which show for various amounts of fuel release, the time-averaged pool fire diameter (D), height (H), emissivity (ϵ_w) and heat flux emitted from the flame($\dot{q}''_f$); the fire duration; and the heat dose to the aircraft skin ($q'' \equiv \dot{q}''_f$. fire duration*) Note that H, D, ϵ, $\dot{q}''_f$ and q'' increase with increase in liquid volume release; while H/D decreases and the fraction radiated (f) is nearly constant. These trends are all reasonable, thus supporting the validity of our model.

Should their be an atmospheric wind, at the time of the fire, the flame would bend downwind. This may reduce slightly the heat transfer to the aircraft skin. Accordingly, we focussed our analyses on the case of zero wind, to be conservative.

Similar calculations were conducted for the three other fuels. Comparisons among the fuels are shown in Figures 7.3 to 7.6 In Figure 7.3, we show the computed fire duration as a function of volume released. Note that the fire duration increases as the fuel volume increases and as the fuel volatility decreases, which is reasonable. LH_2 burns out in approximately 10 seconds, while the other fuel fires may last up to 2 minutes.

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*The heat flux to the top of the aircraft skin is equal to the flux emitted by the flame because of the engulfment of the aircraft in the fire (i.e., the view factor = 1).

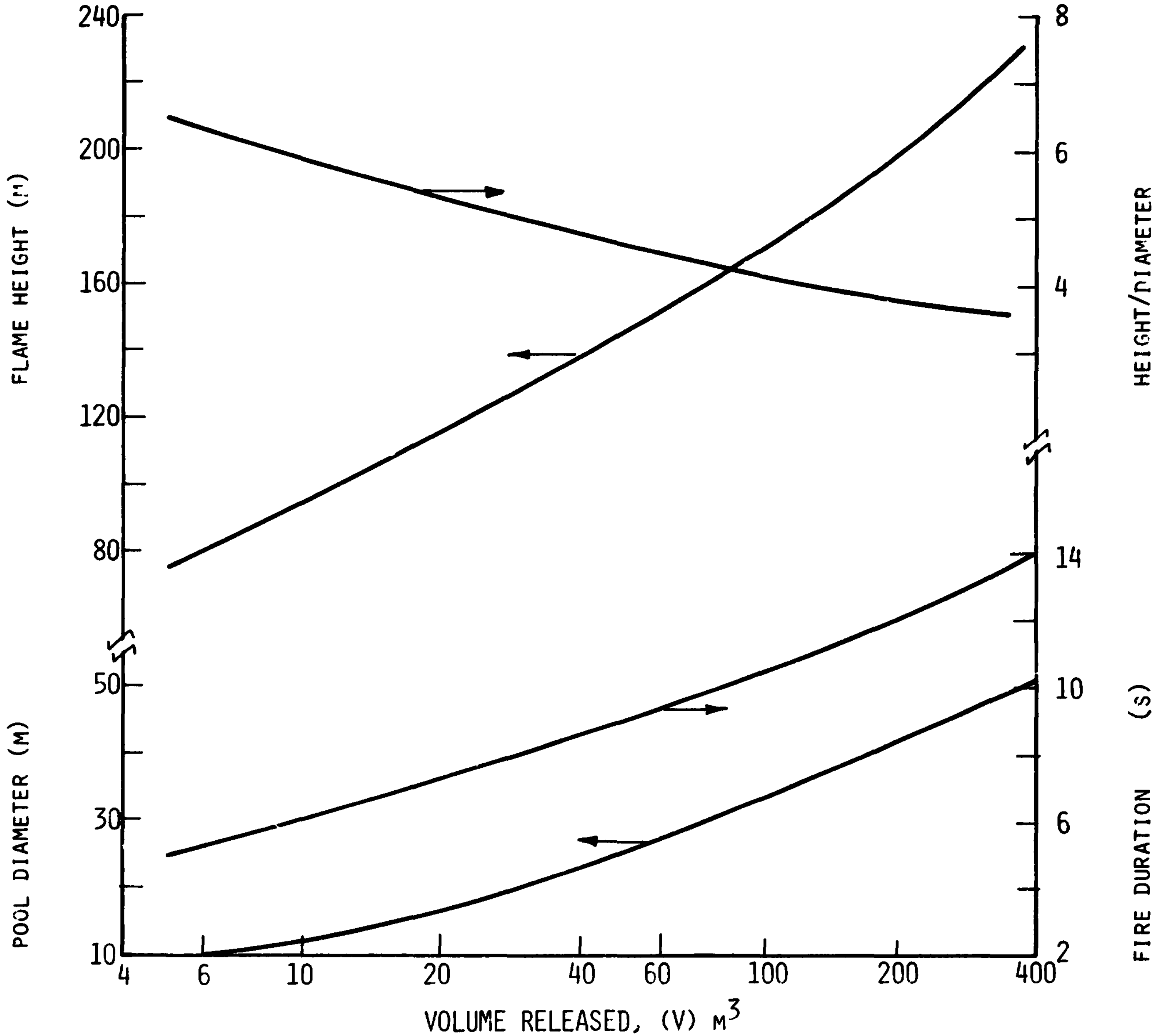


FIGURE 7.1: DURATION AND TIME-AVERAGED DIMENSIONS OF LH_2 POOL FIRES AS A FUNCTION OF INSTANTANEOUSLY-RELEASED LIQUID VOLUME

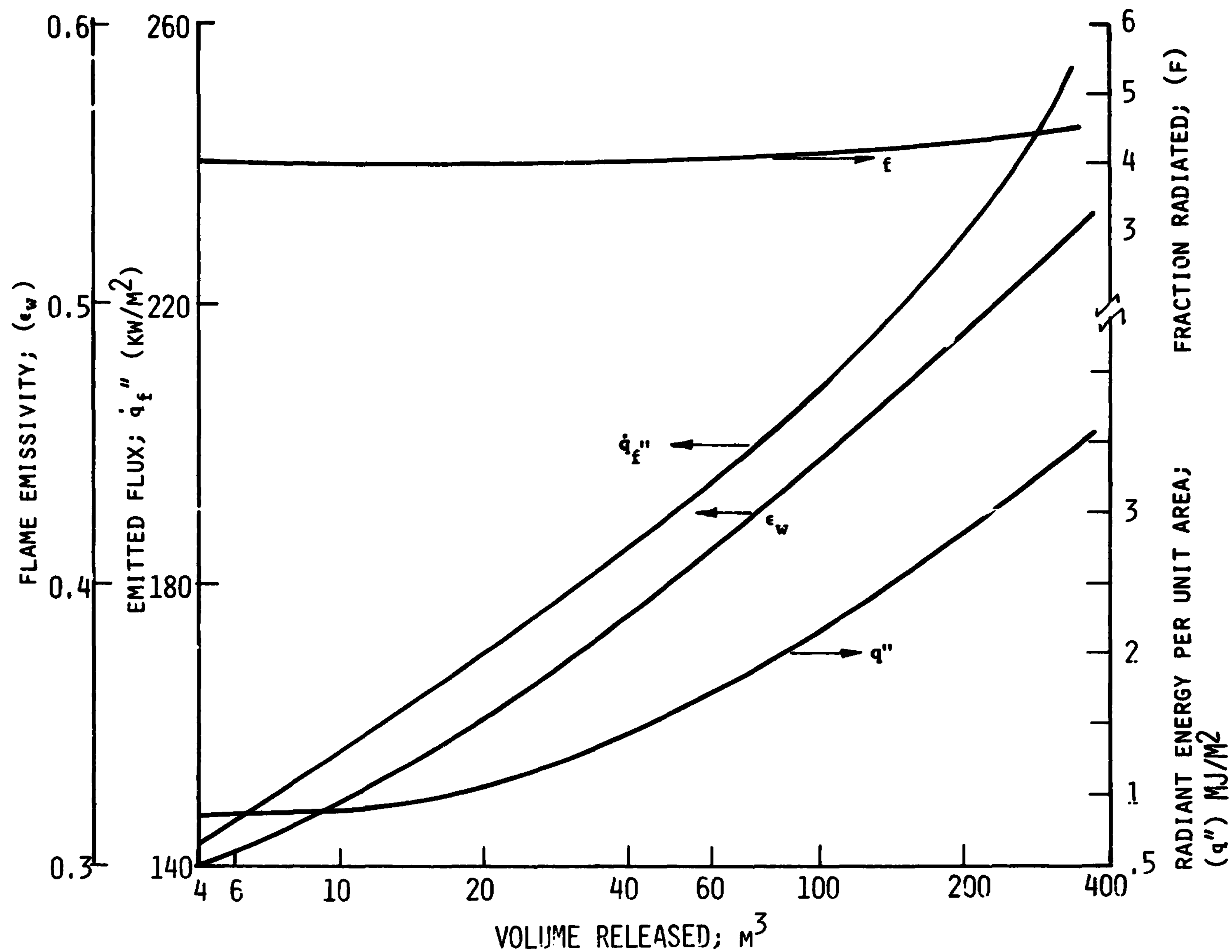
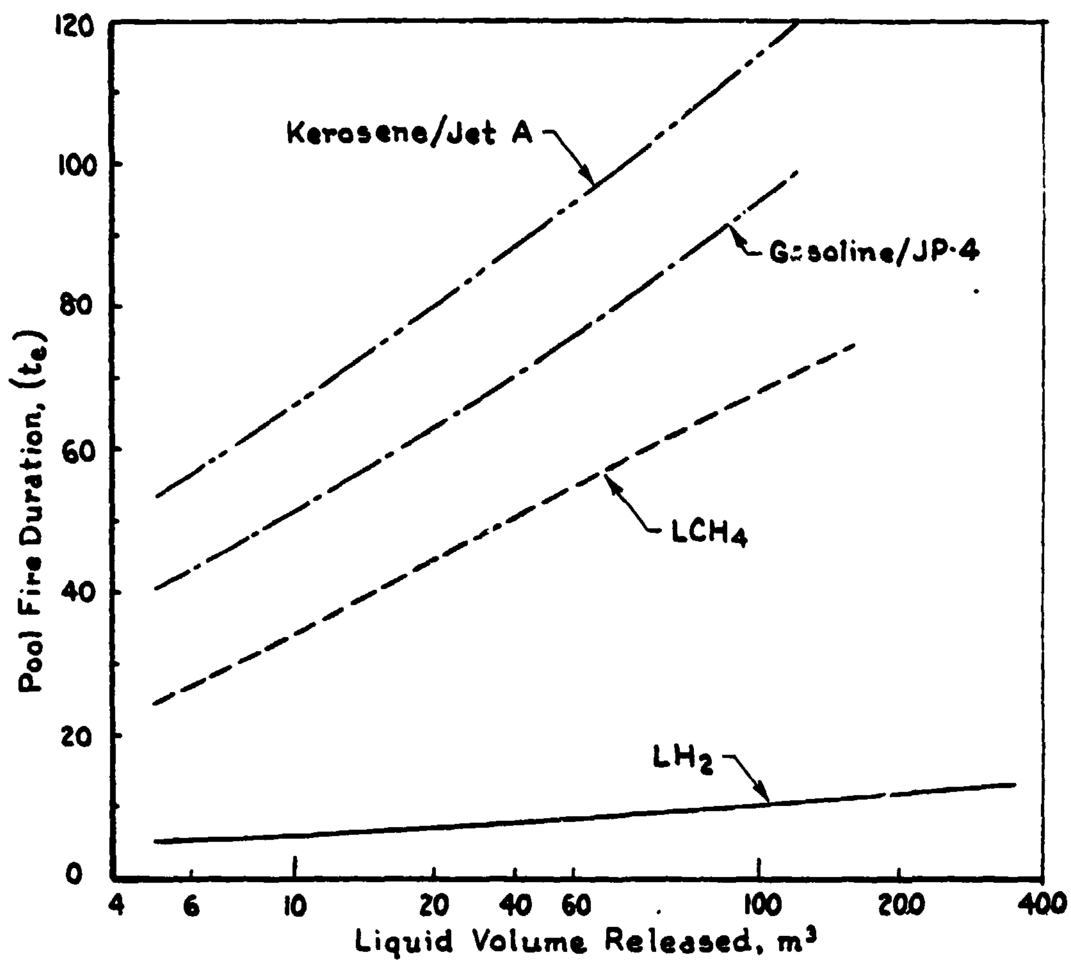
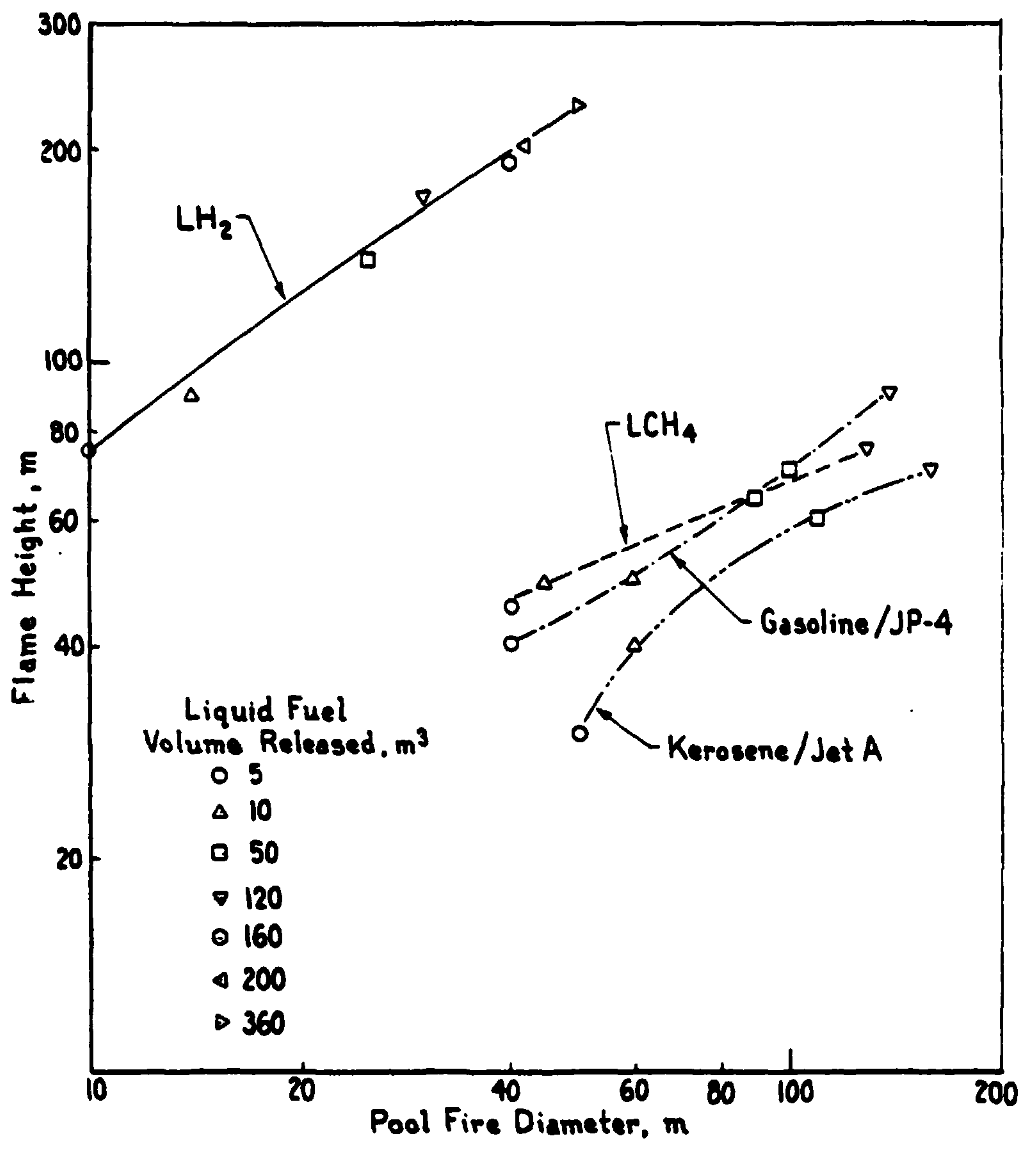


FIGURE 7.2: THERMAL RADIATION FROM LH_2 POOL FIRE AS A FUNCTION OF THE INSTANTANEOUSLY-RELEASED LIQUID VOLUME.



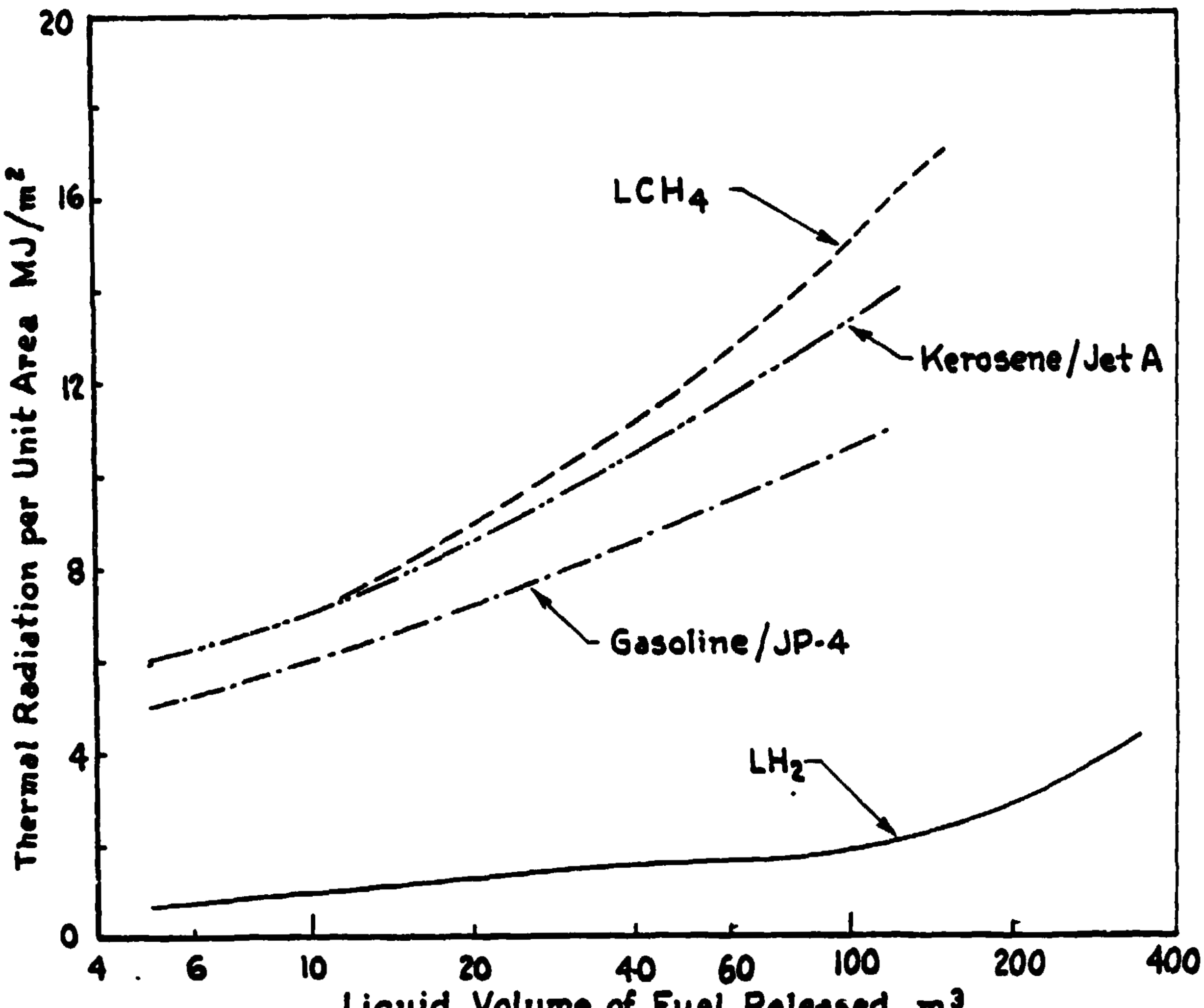
COMPARISON OF THE FIRE DURATIONS FOR POOL FIRES RESULTING FROM THE INSTANTANEOUS RELEASE OF THE FOUR FUELS

FIGURE 7.3



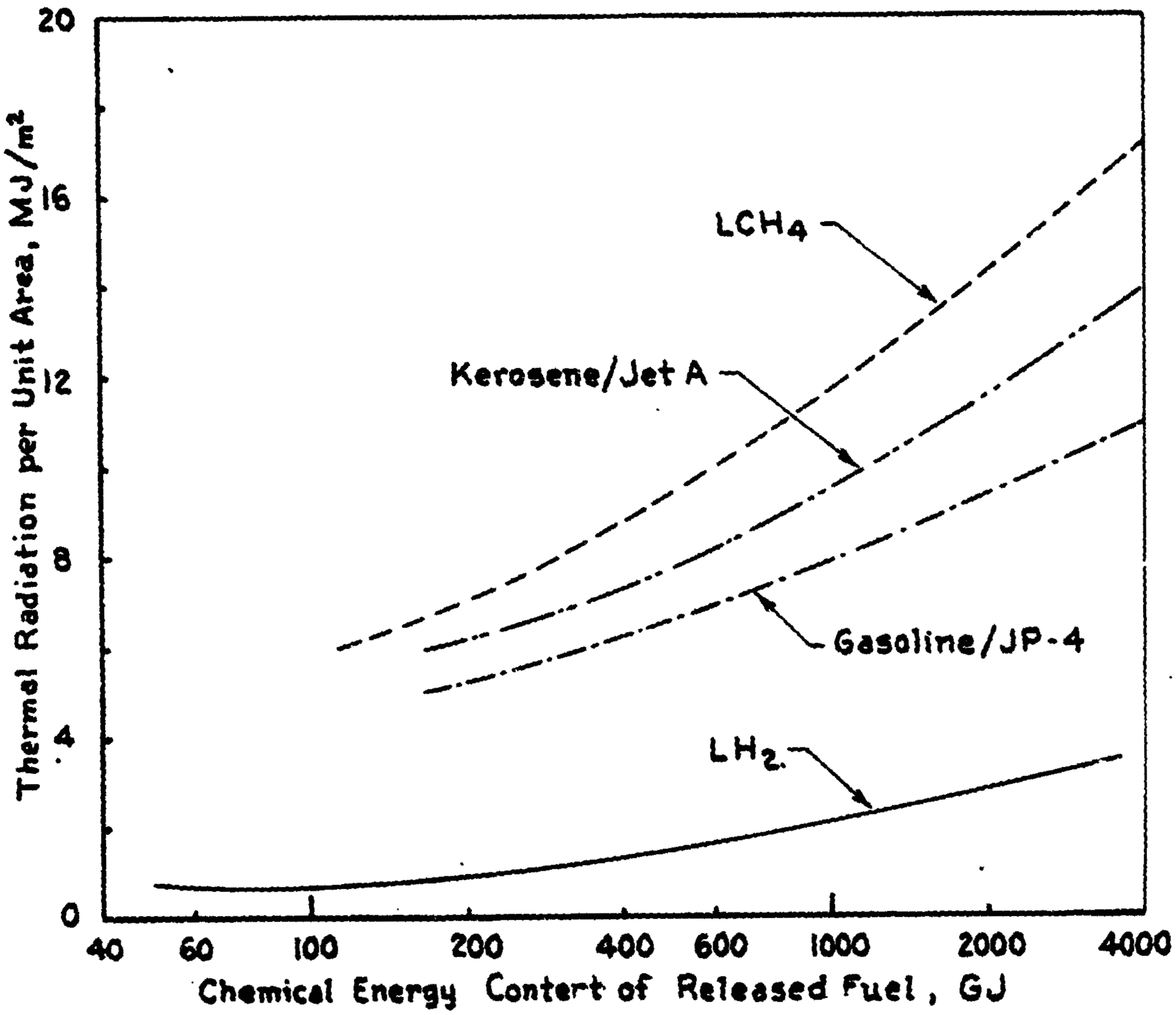
COMPARISON OF THE TIME AVERAGED FIRE SIZES FOR POOLS RESULTING FROM THE INSTANTANEOUS RELEASE OF THE FOUR FUELS

FIGURE 7.4



COMPARISON OF THE TIME-INTEGRATED THERMAL RADIATION FROM POOL FIRES RESULTING FROM THE INSTANTANEOUS RELEASE OF THE FOUR FUELS

FIGURE 7.5



COMPARISON OF THE TIME-INTEGRATED THERMAL RADIATION FROM POOL FIRES RESULTING FROM THE INSTANTANEOUS RELEASE OF THE FOUR FUELS

FIGURE 7.6

In Figure 7.4, we show the time-averaged fire sizes (pool diameter and flame height) corresponding to various fuel release volumes indicated by symbols in Figure 7.4. Note that for a given volume release, the pool fire of LH_2 is significantly narrower and taller than that of the other fuels (this is due to the much larger vaporization rate of LH_2.) Furthermore, the differences among the other three fuels are not significant. Finally, we show in Figures 7.5 and 7.6 the heat dose (q'') to the aircraft skin* over the fire duration. Since the heat dose is the product of the time-averaged heat flux and the fire duration, it combines the effect of fire intensity and duration. The predicted result is a significantly lower q'' for LH_2 than the other fuels -- due mainly to the shorter fire duration. This finding holds when comparing either equal-liquid-volume releases (Figure 7.5) or equal-chemical-energy releases (Figure 7.6).

7.3 CONTINUOUS RELEASE POOL FIRES (SCENARIO 1 or 3)

In this section, we consider small continuous, constant-rate releases covering the ranges computed in Section 4. The releases are assumed to last on the order of 1 to 100 minutes, depending on the flow rate. Immediate ignition results in a pool fire that engulfs a section of the aircraft. The fire lasts as long as the release duration. The fire may be steady or quasi-steady as described in Appendix C.

Similar to the previous section, we computed the pool diameters and flame heights as shown in Figure 7.7. Note that LH_2 fires are typically smaller and taller than those of the other fuels due to higher evaporation rates. Furthermore, the differences between the other fuels are not very significant. These results are similar to those for the instantaneous release pool fires.

In Figure 7.8, we show the emitted heat flux by the flame for the four fuels and for a range of liquid release rates.

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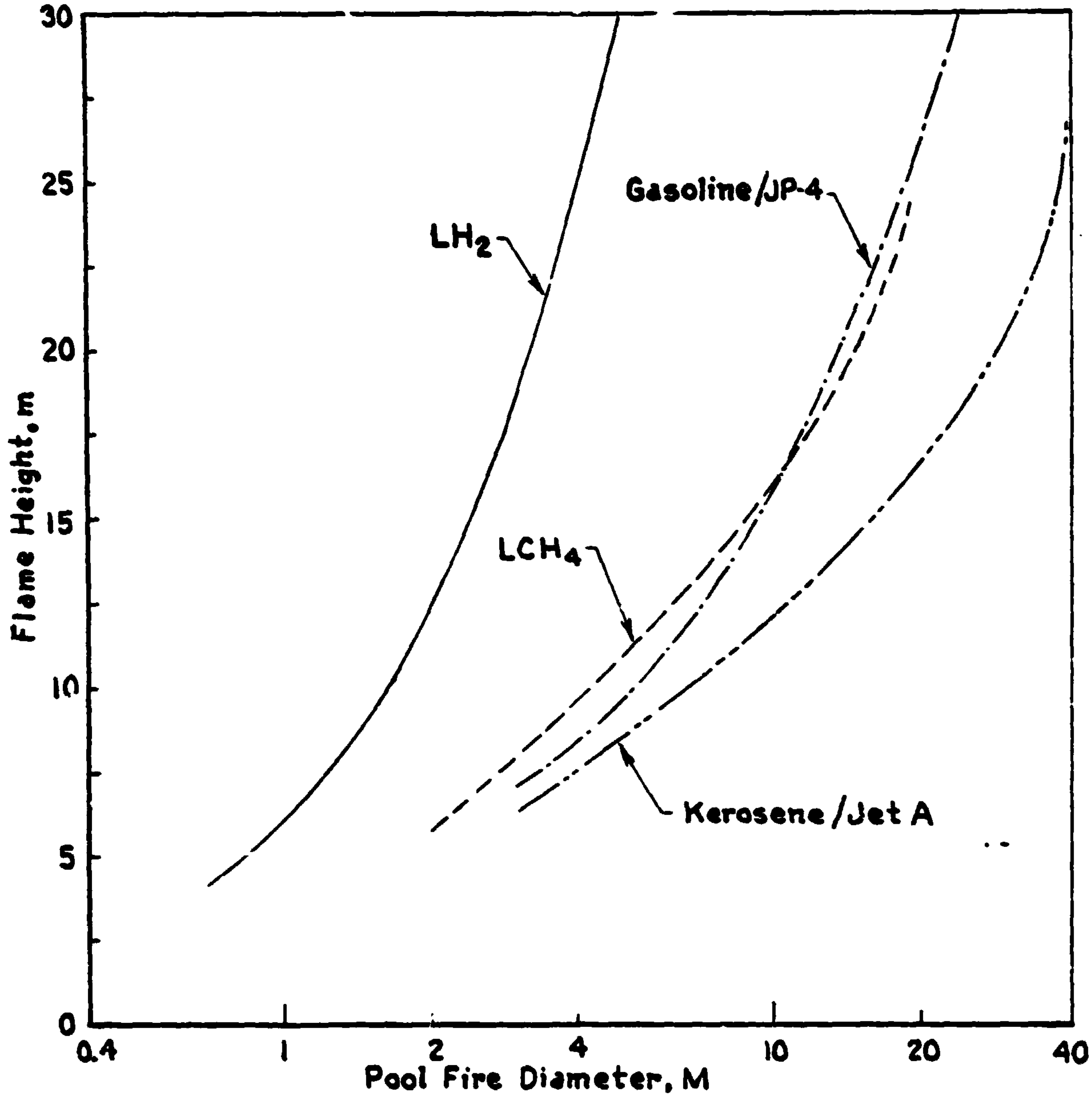
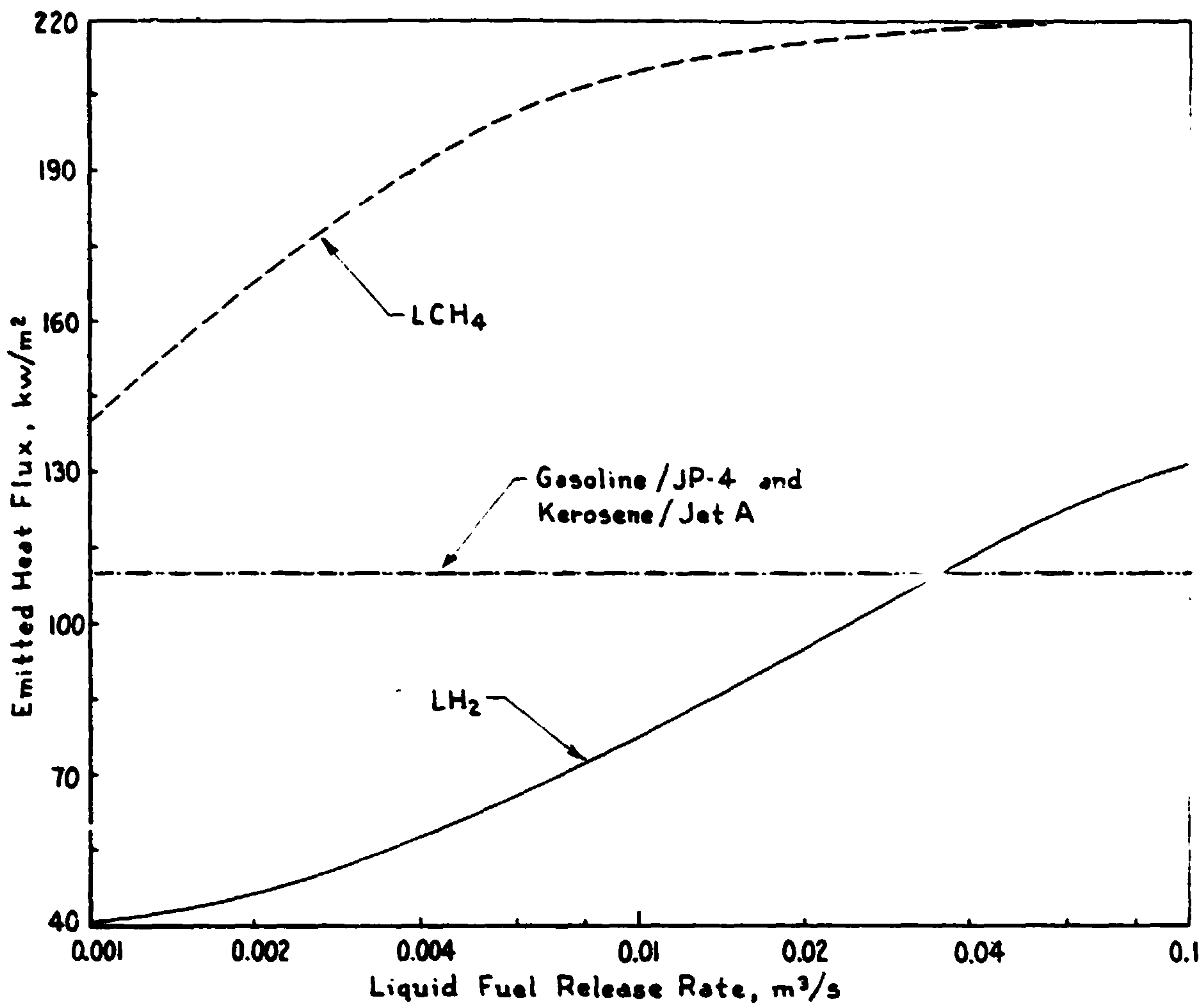
*At the top of the aircraft skin, where the flux is expected to be highest.



COMPARISON OF THE TIME AVERAGED FIRE SIZES FOR POOLS RESULTING FROM THE RELEASE OF THE FOUR FUELS AT CONSTANT RATES (0.001 TO 0.5 m^3/s, LIQUID)

FIGURE 7.7



COMPARISON OF THE EMITTED HEAT FLUXES FROM POOL FIRES RESULTING FROM THE RELEASE OF THE FOUR FUELS AT CONSTANT RATES

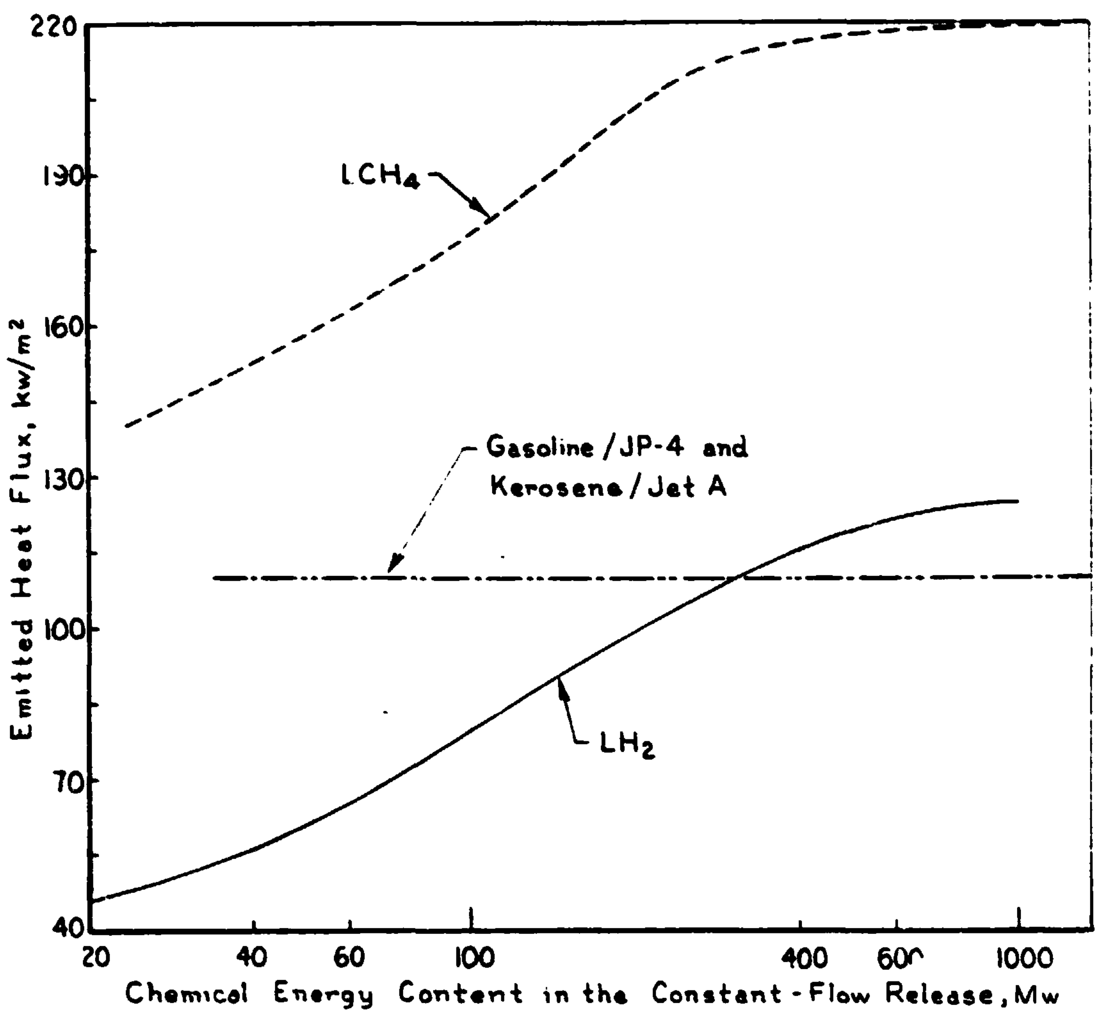
FIGURE 7.8

As the flame size increases, we expect the emitted heat flux first to increase and then becomes constant when the flame is optically thick. This can be inferred from Figure C.1 in Appendix C. For the range of flow rates and corresponding fire sizes of Figure 7.8, the optically thick limit is:

- not reached for LH_2
- reached only at large flow rates for LCH_4
- reached throughout for gasoline/kerosene

Furthermore, small hydrogen fires emit little radiation compared to the other fuels. However, large fires could emit more due to the increase in the flame emissivity and the higher flame temperature. Similar results are obtained when compared on the basis of equivalent-chemical-energy-release rates (see Figure 7.9).

On the qualitative side, the results are consistent with our intuitive expectations. On the quantitative side, the heat flux from LH_2 continuous-release pool fires can be at worst comparable to that from gasoline or kerosene; while it is lower than that from LCH_4.



COMPARISON OF EMITTED HEAT FLUX AS A FUNCTION OF THE CHEMICAL ENERGY IN THE RELEASE (CONSTANT-FLOW POOL FIRES)

FIGURE 7.9

8. CONCLUSIONS AND RECOMMENDATIONS

In this study, we compared crash fire hazards of mission equivalent, 400 passenger, Mach 0.85, 5500 n. mile range aircraft for three types of fuel. These fuels were liquid hydrogen, liquid methane, and conventional jet fuel. The two cryogenic-fueled designs had tanks located in the fuselage; the conventional fuel aircraft had wing fuel tanks. All the designs were based on published Lockheed studies.

For purposes of comparison, we considered four crash scenarios ranging from minor releases to a catastrophic crash. In each scenario, the potential fuel-release and crash fire consequences were compared for the three types of fuels.

Our basic conclusion is that the crash fire hazards are not significantly different when compared in general for the three fuels, although some fuels showed minor advantages in one respect or another. Specifically;

- For fireball post crash scenarios, LH_2 showed relatively lower hazard zones at grade than did conventional fuels and LCH_4 (in that order). This effect is apparent whether the comparison is made on the basis of total fuel volume released or on the basis of equivalent chemical energy content of the fuel released. This is due to the rapid burning of the hydrogen, the smaller fireball size, and the lower emissivity of the hydrogen flame.
- For fuel releases resulting in pool fires, LH_2 also produces smaller hazard zones than the other fuels, on either a volume or energy content comparative basis except for the largest spill sizes where the hazard zone may be slightly higher than that for conventional fuel - but still substantially less than that for LCH_4. Again, the LH_2 fire burns out very quickly, has a smaller diameter (although taller) flame and a lesser emissive power except at very large spill sizes.

- Dispersing aerosol is potentially a problem for all three fuels. Aerosol formation was not treated comparatively because it is so dependent on the specifics of particular crash conditions.

- For the two cryogenic fuels, downwind dispersion of vapors from unignited fuel spills is a potential problem. One might expect LCH_4 to be more likely to disperse downwind near grade; LH_4 might be more likely to rise. However, with aerosol formation, both dispersing clouds could remain near grade.

- Because of the wider flammability limits, more fuel is likely to be flammable at any time in a dispersing LH_2 vapor cloud than in an equivalent LCH_4 vapor cloud. However, this increases the chance of earlier ignition in a dispersing LH_2 cloud and may reduce the extent of downwind vapor fire damage.

- Smaller spills of LH_2 and LCH_4 are likely to disperse as neutrally buoyant plumes.

- Considerable uncertainty exists in prediction of downwind dispersion distances for large LCH_4 spills because of limited experimental data and the complexity of the physical effects involved in developing a theoretical model. Far less data are available for LH_2 spills.

- In severe crashes, fire is so likely that theoretical flammable vapor dispersion with delayed ignition is not considered a credible threat at large distances from the crash.

- LH_2 is more likely to cause blast effects due to accumulation and ignition in confined spaces. This problem can be minimized by careful design, monitoring, provision of inerting systems, and design with secondary barriers to contain small leaks.

In summary, our comparative evaluation for historically observed crash damage scenarios applied to mission equivalent aircraft shows that LH_2 offers survivability benefits in most cases where a fire occurs rapidly. The advantages and disadvantages in other respects are relatively minor and difficult to quantify. However, from a crash fire

hazard standpoint, LH_2 does not appear to be a significantly more hazardous fuel than conventional jet fuels and LCH_4. In some respects, it offers lesser hazards. Thus, pending some future research and development work, we see no crash fire hazard situations which should discourage development of a LH_2-fueled aircraft.

From our evaluation, we recommend that additional safety studies be performed to clarify some of the remaining uncertainties relating to LH_2 hazards. In particular:

- Additional dispersion and fire tests would be desirable to confirm the conclusions drawn in this study, which are based on the current state-of-the-art. For example, pool fire tests with an instrumented fuselage can be conducted to test the validity of our predictions in Section 7.
- Comparisons between future LH_2 tests and planned LCH_4 (LNG) tests, under DOE sponsorship at Jackass Flats, Nevada, should be made.
- Second generation fire and dispersion models should be developed, based on theory and results of experiments.

Further, should the development of a LH_2 aircraft proceed, some technological improvements should be given priority, for example:

- Further studies to develop optimum design and systems for LH_2 aircraft are needed. Crashworthiness should be an important consideration in design.
- Since component reliability is very important in preventing minor leaks with potential for creating a serious incident or accident in a LH_2 aircraft, attention should be focussed on further development work on the following components:
  - Less expensive pumps ($5,000 range)
  - Improved pump seals with a longer operating life (present seals are designed for only a few hours of operation)

- Evaluation of new types of fuel transfer systems to minimize the change of any leakage (pump seals, valve packings, etc.)
- Improved lightweight and strong storage systems
- Optimized LH_2 combustors

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APPENDIX A

DESCRIPTION OF AIRCRAFT FUEL SYSTEMS AND CALCULATIONS OF FUEL RELEASE RATES

A.1 INTRODUCTION

In this Appendix, we present a description of the three fuel systems under study, and an estimate of the fuel release rates for each system and each accident scenario.

The aircraft considered are the three mission-equivalent aircraft selected for analysis in Section 2 of the main report. These aircraft are fueled by LH_2, LCH_4 and Jet A. (For the purpose of the fuel release analysis, we need not differentiate between Jet A and gasoline or JP-4.)

The accident scenarios considered are those described in Section 4. They cover a minor fuel release, a massive release with the aircraft at rest, a massive release with the aircraft in motion and a catastrophic release. These scenarios have been associated with specific failure modes/events such as vibration, strained maneuver, engine burst, sheared engine pad, failed thermal insulation, sheared wing, broken fuselage and fragmented aircraft. The fuel release rates were calculated for these failure modes/events. These rates have already been presented in a summary form in Table 4.3 of the main report.

A.2 LH_2 FUEL SYSTEM

A.2.1 SYSTEM DESCRIPTION

The LH_2 aircraft fuel system details are taken from the Lockheed Study[A.1] for a 400 passenger aircraft with a range of 5500 nautical miles operating at a cruise speed of Mach 0.85.

TANKS

The exterior configuration identified above resembles a conventional subsonic jet passenger aircraft as shown in Figure A.1. The interior configuration, however, is significantly different in that the fuel is stored within the fuselage. Two fuel tanks are provided: the forward tank is located between the flight crew compartment and the passenger compartment; the rear tank is located in the tail section of the fuselage behind the

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Source: Reference A.1

FIGURE A.1: SUBSONIC LH_2-FUELED TRANSPORT

passenger compartment as shown in Figure A.2. Each tank has a central bulkhead dividing the tank into two fuel compartment. The fuel tanks are integral* with the fuselage and are insulated with glass microspheres placed in an evacuated jacket around the tank. Each fuel tank is numbered from 1 to 4 corresponding to the engine to which it normally supplies fuel. The left and right inboard engines are numbered 2 and 3, respectively; outboards are 1 and 4.

The aircraft has a gross fuel load of 56,460 pounds. This is distributed equally in the four fuel tanks at 14,115 pounds each. Because two tanks are contained in one tank envelope and interconnected, the complete failure of either the forward or aft fuel storage will contribute up to a maximum of 28,230 pounds of LH_2 to the hazard.

BOOSTER PUMPS

Pumps are required to deliver the fuel from the tanks to the engines in order to meet the Net Positive Suction Head (NPSH) requirements of the high pressure engine pumps. The pumps are of the centrifugal type located within the tanks. Each of the four tanks contains three pumps of which two are powered during flight operations at all times from separate power sources. Each pump has a design pressure rise of 45 psi at a mass flow of 0.774 lb/sec. and each is driven by a variable speed motor that is controlled by the engine requirement. Thus, the pump pressure rise and flow can vary over a wide range.

LINES

The booster pumps transfer the fuel from the tanks to their respective engines through 1 inch diameter stainless steel lines. The lines are thermally insulated with 1.5 inches of closed cell polyurethane foam encased in an aluminum jacket. Evacuated double bellow lines with an outer braided cover are used where line flexibility is required.

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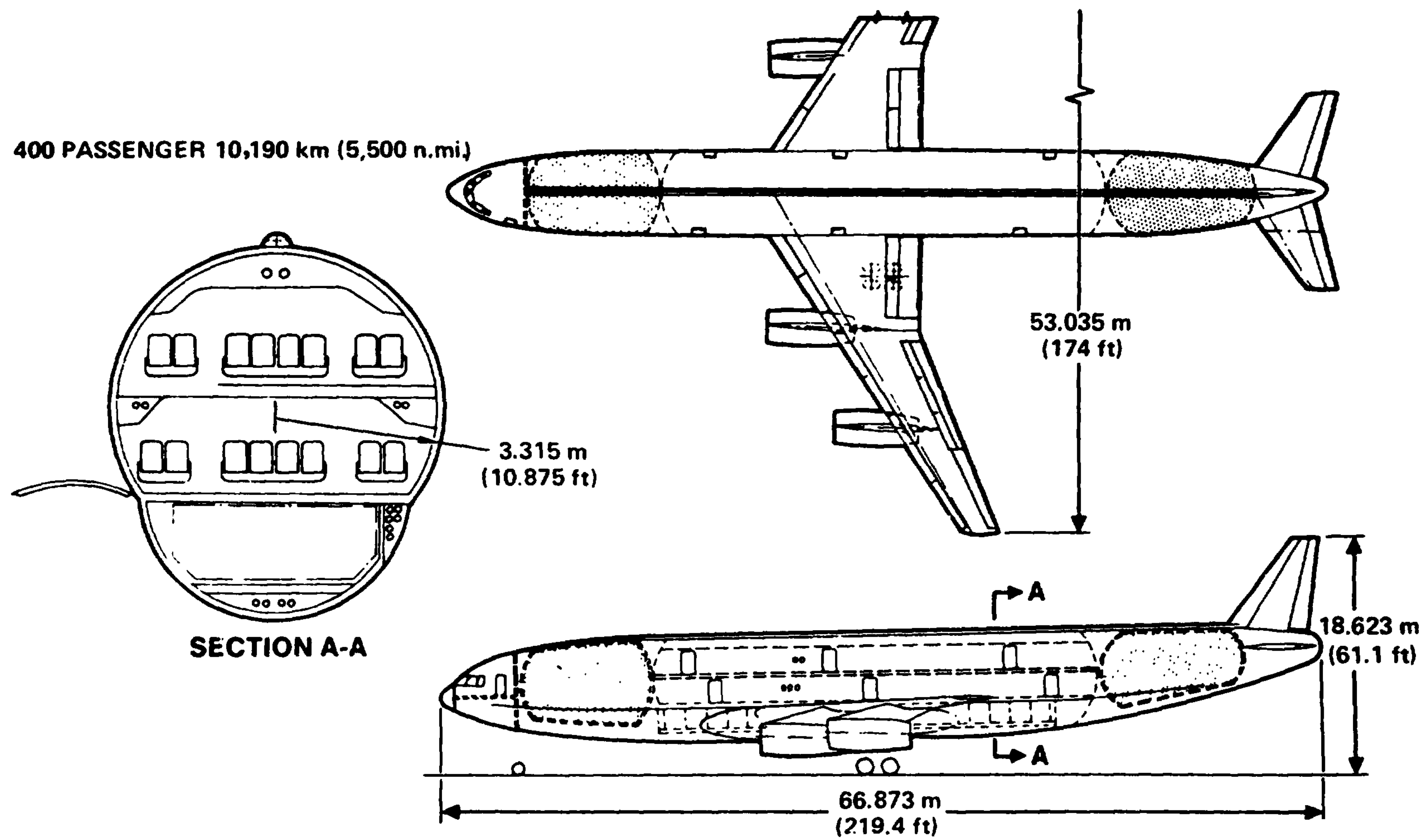
*Integral indicates that the circular sections of the tank form a part of the fuselage structure and therefore are designed to sustain and transmit all the forces developed in the fuselage during the mission.



Source: Reference A.1

FIGURE A.2: LH_2-FUELED PASSENGER TRANSPORT

The fueling system is shown schematically in Figure A.3 and its arrangement in the aircraft is shown in Figure A.4. The fuel from any tank can be transferred to engines other than its assigned engine through a crossfeed valving arrangement located as indicated in Figure A.4, Detail A.

FILL, DRAIN AND VENT

All fueling, defueling and venting of the fuel tanks is performed at the aircraft tail. The lines for these operations to the tanks from this location are mounted in a tunnel over the fuselage at the vertical centerline, as shown in Figure A.5 (Detail E). The lines are vacuum Jacketed to provide thermal insulation.

A.2.2 LH_2 PIPE LINE BREAK

A centrifugal type booster pump located in the LH_2 tanks transfers the LH_2 fuel to engines where it is pumped to the combustion chamber pressure at a design flow of 0.77 lb/sec. In the event that the fuel line is cleanly severed at the outboard engines, the discharged fuel will flow at about 1.3 lb/sec. single phase liquid flow based upon an equivalent line length* of 300 feet. The mass flow from a line of shorter length (severed at a point closer to the tank than the outboard engines) can be estimated from the following equation:

$$W = \frac{1.3}{\sqrt{(F_1)}} \quad \left[\frac{lb}{sec}\right] \qquad (A.1)$$

Where:

F_1 is the length factor in fractions of 300 feet.

For example, a LH_2 fuel line cleanly severed at the root of the wing has an estimated flow of 1.8 lb/sec., assuming that the line length is half of the length to the outboard engines. As shown in Figure A.4, two fuel lines pass through the wing root area. Thus, the expected flow, when a single wing is severed, is 3.6 lb/sec., and for two severed wings is 7.2 lb/sec. Loss of all four engine pods is estimated to produce a total flow of 5.2 lb/sec., 1.3 lb/sec. from each engine feed line. These values are listed in Table 4.3, which summarizes the fuel leak values for the three aircraft and which will be discussed in Section 4.

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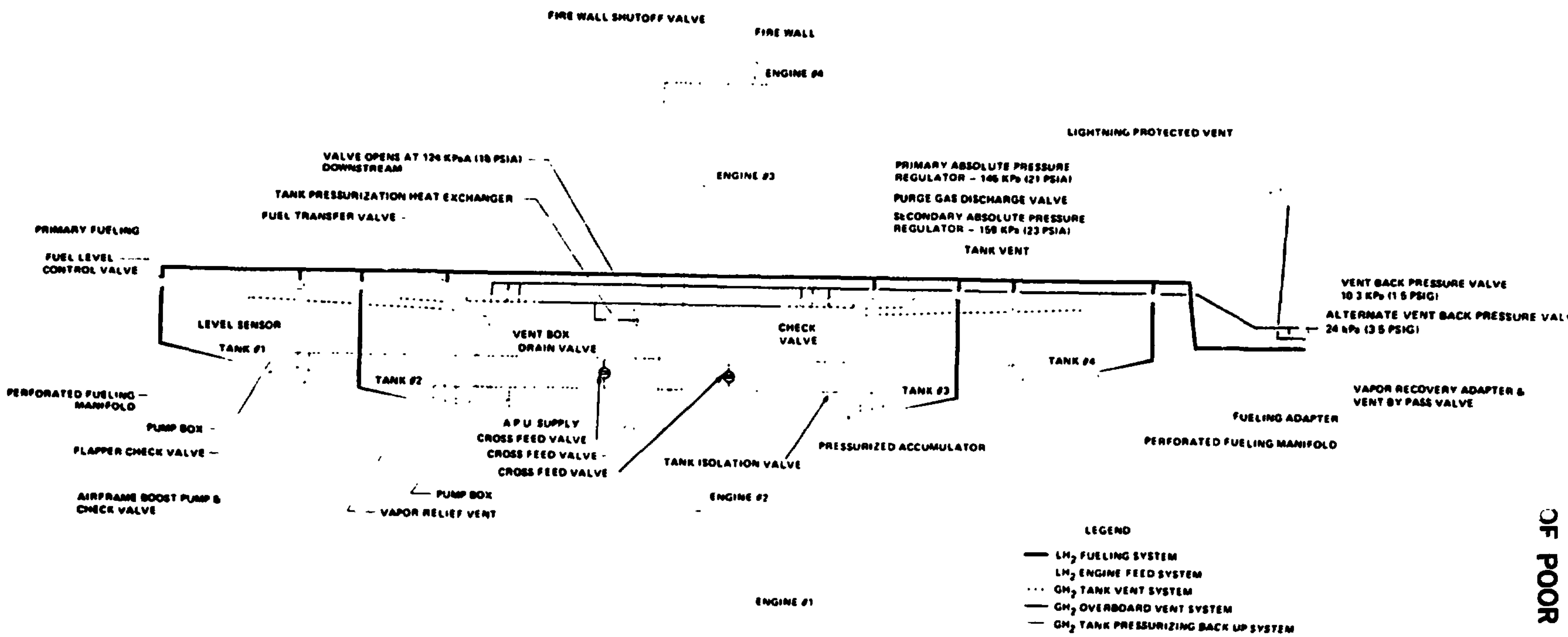
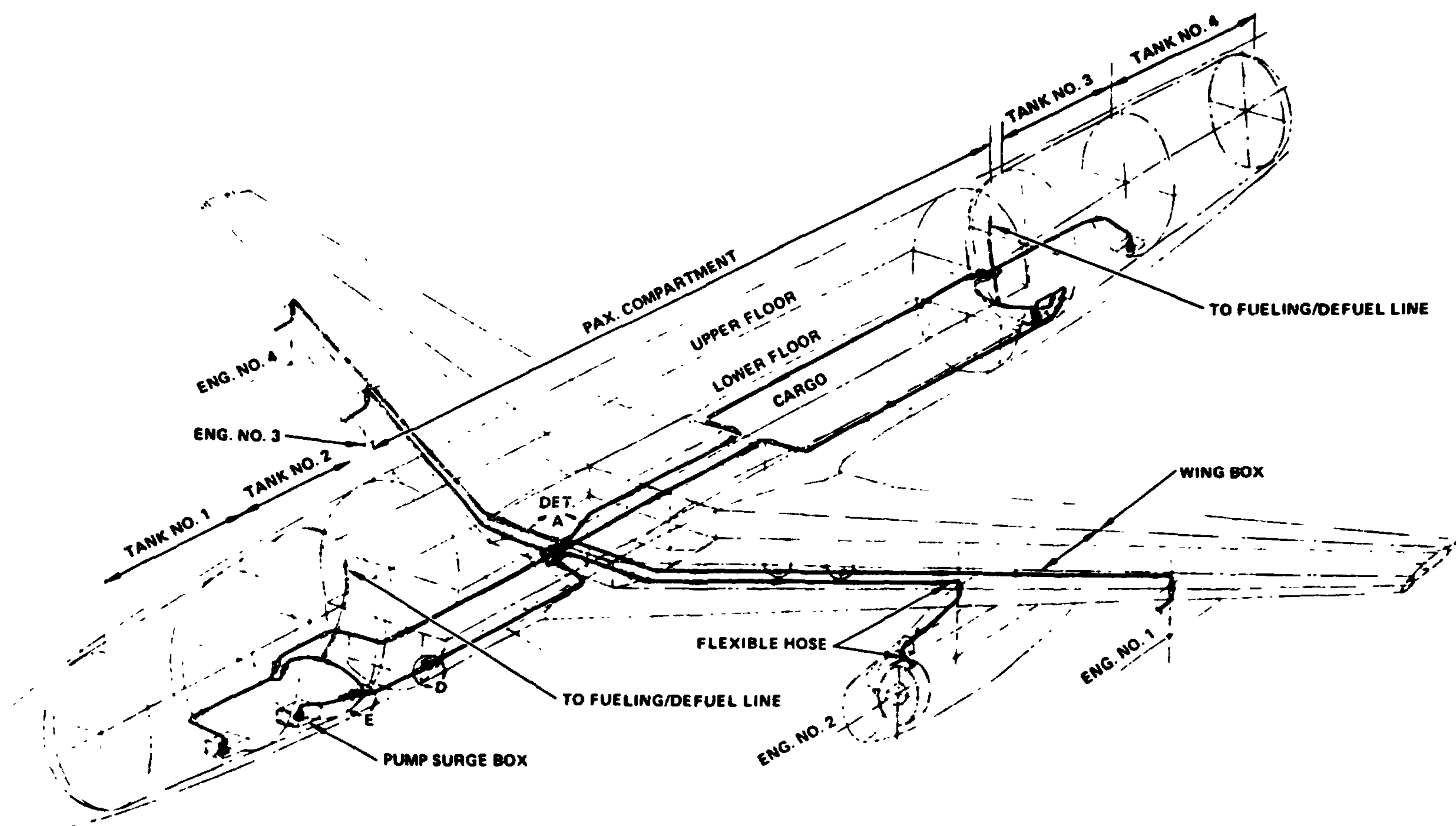
*The longest line length between tank and engine is estimated to be 150 feet. The equivalent length is assumed to be twice the actual line length or about 300 feet to account for elbows and fittings in the pressure-flow calculations.



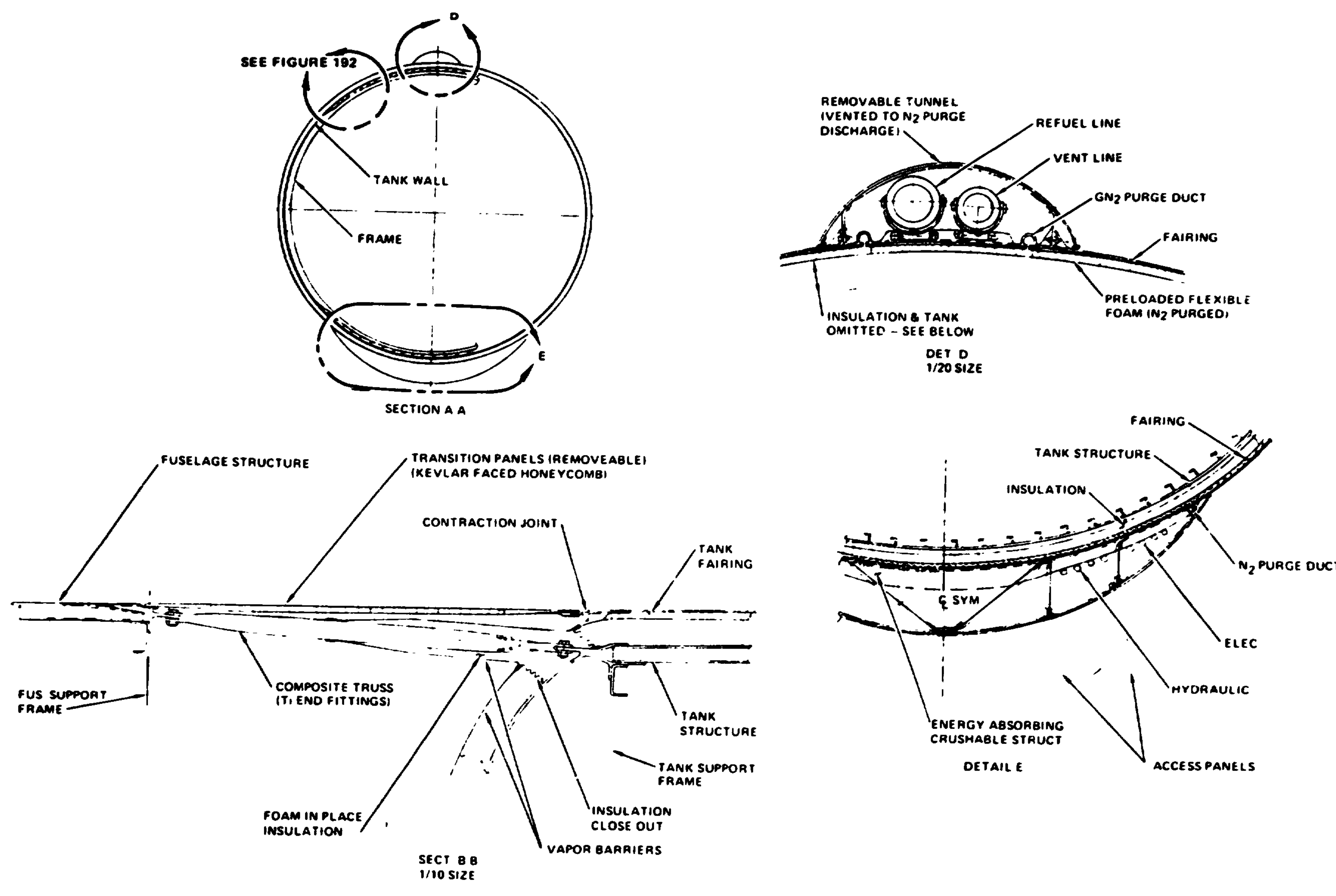
Source: Reference A.1

FIGURE A.3: LH_2-FUEL SYSTEM SCHEMATIC



Source: Reference A.1

FIGURE A.4: LH_2 ENGINE FUEL SUPPLY SYSTEM



Source: Reference A.1

FIGURE A.5: LH_2 TANK AND LINE DETAILS

The LH_2 flow of 1.3 lb/sec. from a single severed line is the steady state rate discharging directly to the atmosphere, which can also be used as the initial discharge rate from the line into the aircraft interior. This rate may decrease with time as the pressure generated by the vaporized LH_2 in the closed compartment increases unless there is a structural failure in the compartment walls causing it to open to atmosphere.

It should be noted that the fuel lines will be housed in well protected areas of the fuselage and wing structure. Damage to them from outside of the aircraft will only occur if the structure is severely damaged or penetrated. Thus, a break in the fuel line will vent to the atmosphere. However, when the fuel lines are damaged by vibration and structural strains, for example, they may discharge into the interior compartments of the aircraft. Vaporization of LH_2 within these compartments will pressurize them and can cause structural damage. Further, with air and potential ignition sources in the failed compartments, a fire is likely to occur.

A.2.3 FUEL TANK LEAK

An opening in the tank wall will release liquid to the outside or to the inside depending on its location. These tanks are designed for 23 psi ullage pressure (relief valve setting). At landing or take-off, there is a differential pressure from inside to the outside of 8.3 psi max. An opening in the tank to the outside, equivalent to the flow area of the transfer lines, will produce a flow of nearly 2 lb/sec.* As this flow is directly proportional to the area of the opening, the flows for larger or smaller openings can be determined. Flows from larger openings are tabulated below for equivalent diameters from 1 to 32 inches:

Equivalent Opening Diameter (in.)	LH_2 Discharge Rate (lb/sec.)
1	2
2	8
4	30
8	130
16	510
32	2100

*This neglects the effects of gravity head and inertia on the liquid. These effects are small compared to the ullage pressure.

An opening in the tank end walls leading to the spaces inside of the aircraft skin can result in gas generation and pressurization of the spaces. One end of forward tank leads to the cockpit and the other to the passenger compartment. The forward end of the aft tank also leads to the passenger compartment; the aft end leads into the tail which remains vented at all times to the atmosphere. The hazards to personnel and passengers resulting from leaks into these spaces should be examined. A further hazard may be the cold shocking of the mechanical, electrical and hydraulic components in these areas which may induce other failures.

A.3 LCH_4 FUEL SYSTEM

A.3.1 SYSTEM DESCRIPTION

The LCH_4 aircraft fuel system are from the Lockheed Study[A.2] for a 400 passenger aircraft with a range of 5500 nautical miles operating at a cruise speed of Mach 0.85. This mission is identical to the mission for the comparison LH_2 aircraft.

TANKS

The exterior and interior configurations of the LCH_4 aircraft are similar to those of the LH_2 aircraft shown in Figure A.1. The LCH_4 aircraft dimensions and fuel tank placement are shown in Figure A.6. The forward fuel storage is a non-integral spherical tank with a fore-to-aft partition dividing the fuel into two equal volumes. The tank is supported within the fuselage in four trunnions, two on the vertical centerline (of the tank and two on the horizontal centerline (perpendicular to the flight path). The tank is thermally insulated with a 2-inch thickness of closed cell polyurethane foam. The aft fuel tank is integral with the fuselage. It has a truncated conical shape, ellipsoid ends and a partition dividing it into two equal fuel volumes. The tank is thermally insulated with 1.75 inches of closed cell polyurethane foam covered with a vapor barrier. This, in turn, is covered with a nitrogen purged open cell foam which supports the aircraft fairing.

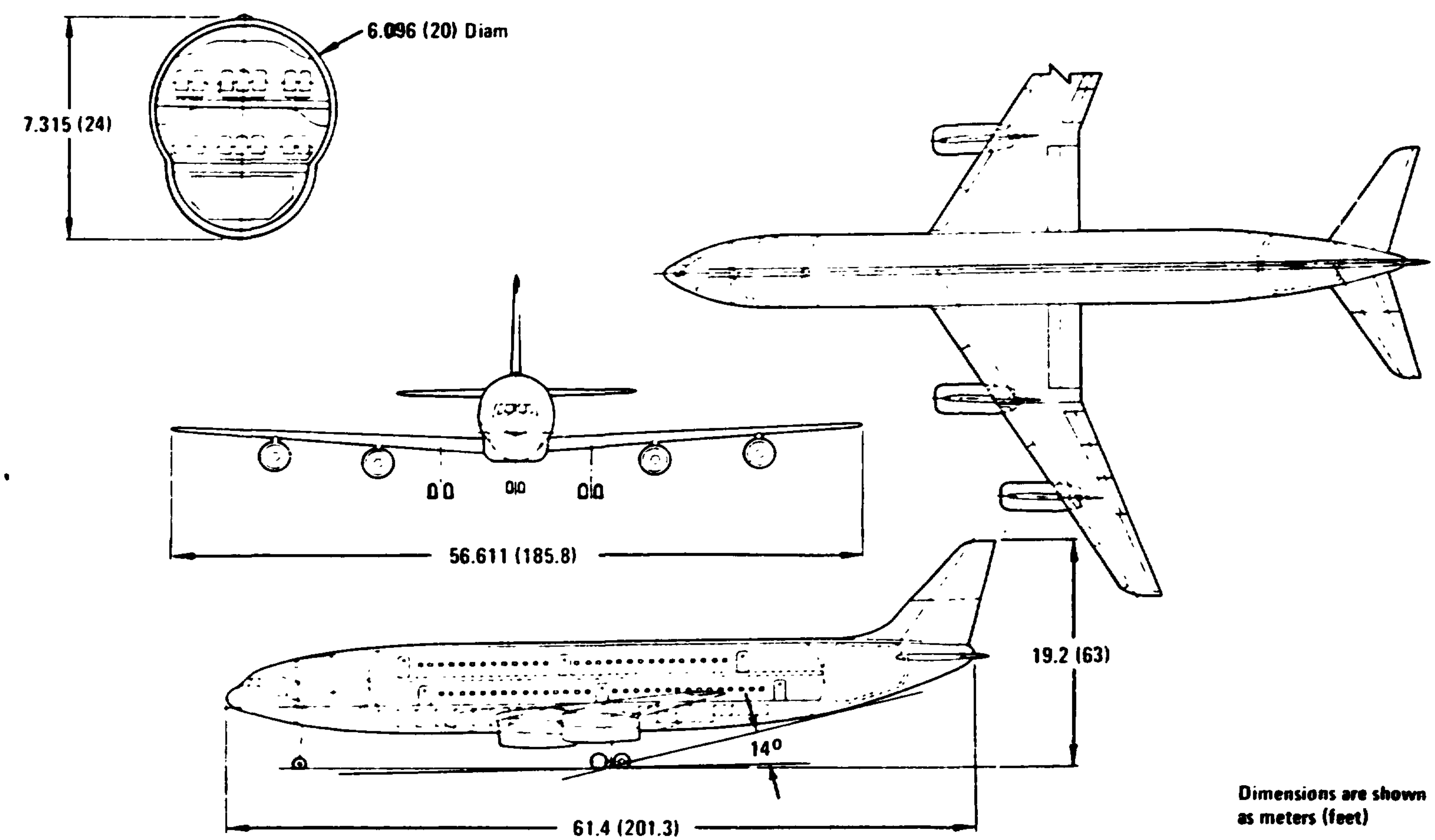


FIGURE A.6: LCH_4 FUELED PASSENGER TRANSPORT

A.3.2 LCH_4 FUEL LINE BREAK

A centrifugal type booster pump located in the LCH_4 fuel tanks transfers the LCH_4 fuel to engines where it is pumped to the combustion chamber pressure at a design flow of 2.26 lb/sec. In the event that the fuel line is cleanly severed at the outboard engines, the discharged fuel will flow at about 3.5 lb/sec. single phase liquid flow based upon an equivalent line length* of 300 feet. The mass flow from the line of shorter length (severed at a point closer to the tank than the outboard engines) can be estimated from the following equation:

$$W = \frac{3.5}{\sqrt{(F_1)}} \quad \left[\frac{\text{lb}}{\text{sec}}\right] \qquad \text{(A.2)}$$

Where:

F_1 is the length factor in fractions of 300 feet.

For example, a LCH_4 fuel line cleanly severed at the root of the wing has an estimated flow of 5 lb/sec., assuming that the line length is half of the length to the outboard engines. As shown in Figure A.7, two fuel lines pass through the wing root area. Thus, the expected flow, when a single wing is severed, is 10 lb/sec., and for two severed wings is 20 lb/sec.

The LCH_4 flow of 3.5 lb/sec. from a single severed line is the steady state rate discharging directly to the atmosphere, which can also be used as the initial discharge rate from the line into the aircraft interior. This rate may decrease with time as the pressure generated by the vaporized LCH_4 in the closed compartment increases.

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*The longest line length between tank and engine is estimated to be 150 feet. The equivalent length is assumed to be twice the actual line length or about 300 feet for pressure-flow calculations.

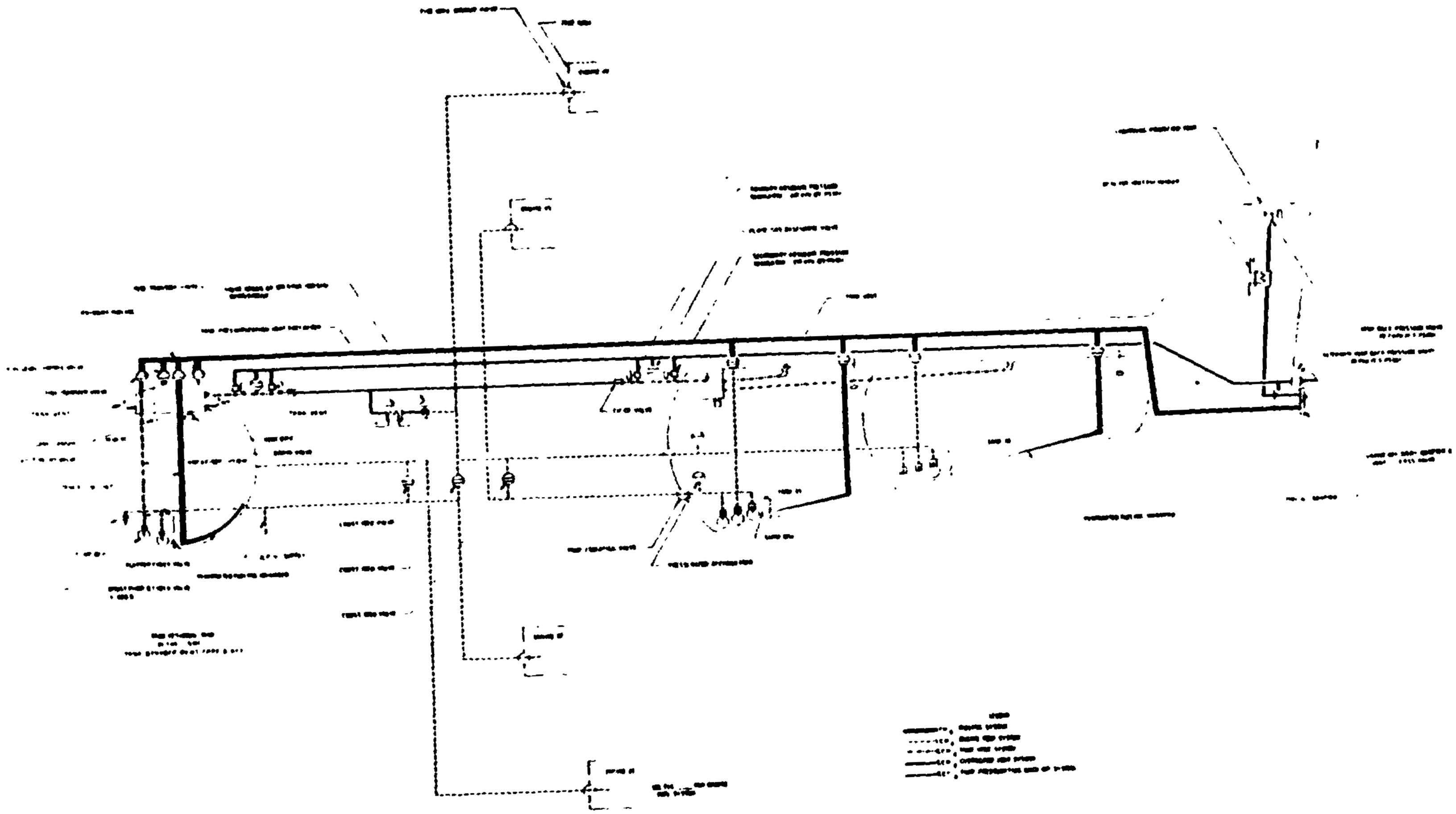


FIGURE A.7: LCH_4 FUEL SYSTEM SCHEMATIC

The fuel lines of the LCH_4 aircraft, like those of the LH_2 aircraft, will be housed in well protected areas of the fuselage and wing structure. Damage to them from outside of the aircraft will only occur if the structure is severely damaged or penetrated. Thus, a break in the fuel line will vent to the atmosphere. However, when the fuel lines are damaged by vibration and structural strains, for example, they may discharge into the interior compartments of the aircraft. Vaporization of LCH_4 within these compartments will pressurize them and can cause further structural damage. Further, with air and potential ignition sources in the failed compartments, a fire is likely to occur.

The flow from two cleanly sheared lines at the wing root is estimated at 10 lb/sec. This fuel system failure results when the wing is sheared from the fuselage after striking an obstruction. Loss of all four engine pods is estimated to produce a total flow of 14 lb/sec., 3.5 lb/sec. from each engine feed line.

A.3.3 FUEL TANK LEAK

An opening in the aft fuel tank wall will release liquid to the outside and possibly into the interior of the fuselage. The forward fuel tank, contained entirely within the fuselage, will release fuel into the fuselage interior when ruptured. These tanks are designed for 21 psi ullage pressure. At landing or take-off, there is a differential pressure from inside to the outside of 6.3 psi max.

The initial rate of dumped LCH_4 will vary depending upon the location of the opening and the fuel tank ullage pressure, as well as positive "G" forces generated by the motion of the aircraft. The ullage pressure can vary by design in normal operation between 18 and 21 psig. Because the tank had a diameter of about 16 feet, the pressure at the bottom of the tank, due to the static head of liquid, will vary from 0 to 3 psi depending upon liquid level. At any other location on the tank, the variation will be less than 0-3 psi. Another 0-3 psi must be added to the liquid pressure to allow for a 1 "G" load factor induced by a pitching maneuver. Thus, the minimum and maximum liquid pressures developed across an opening are 0 and 12 psi, respectively, depending on location.

Each fuel tank is numbered from 1 to 4, corresponding to the engine to which it normally supplies fuel. Figure A.7 shows the fuel feed system for the LCH_4 aircraft.

The aircraft has a gross fuel load of 152,000 pounds. This is distributed equally into four fuel tanks at 38,000 each. Because the fuel supply for two engines is carried in one tank envelop and interconnected, the failure of either the forward or aft fuel storage will contribute up to a maximum of 76,000 pounds of LCH_4 to the hazard.

BOOSTER PUMPS

Pumps are required to deliver the fuel from the tanks to the engines in order to meet the Net Positive Suction Head (NPSH) requirements of the high pressure engine pumps. The pumps are of the centrifugal type located within the tanks. Each of the four tanks contains three pumps of which two are powered during flight operations at all times from separate power sources. Each pump has a design pressure rise of 30 psi at a mass flow of 2.26 lb/sec.

LINES

The booster pumps transfer the fuel from the tanks to their respective engines through 1.2 inch diameter stainless steel lines. The lines are thermally insulated with 1.5 inches of closed cell foam encased in an aluminum jacket. Evacuated double bellow lines with an outer braided cover are used where line flexibility is required.

The fueling system is shown schematically in Figure A.7 and its arrangement in the aircraft is similar to Figures A.4 and A.5 for the LH_2 aircraft. The fuel from any tank can be transferred to engines other than its assigned engine through a cross-feed valving arrangement located as indicated in Figure A.4, Detail A.

FILL, DRAIN AND VENT

All fueling, defueling and venting of the fuel tanks is performed at the aircraft tail. The lines for these operations to the tanks from this location are mounted in a tunnel over the fuselage at the vertical centerline, similar to that shown in Figure A.5, for the LH_2 aircraft.

An opening in the aft tank to the outside equivalent to the flow area of the transfer lines will produce a flow of nearly 7.5 lb/sec. As this flow is directly proportional to the area of the opening, the flows for larger or smaller openings can be determined. Flows from larger openings are tabulated below for equivalent diameters from 1.2 to 32 inches:

Equivalent Opening Diameter (in)	LCH_4 Discharge Rate (lb/sec)
1.2	7.5
2	21
4	83
8	330
16	1300
32	5300

An opening in end walls of either tank leading to the spaces inside of the fuselage can result in gas generation and pressurization of the spaces. A further hazard may be the cold shocking of the mechanical, electrical and hydraulic components in these areas which may induce other failures.

A.4 JET A FUEL SYSTEM

A.4.1 SYSTEM DESCRIPTION

The Jet A aircraft fuel system details are obtained from Lockheed[A.2, 3] for a 400 passenger aircraft with a range of 5500 nautical miles operating at a cruise speed of Mach 0.85.

TANKS

The exterior configuration of the Jet A aircraft is similar to that of the LH_2 aircraft shown in Figure A.1. The fuel storage is in the wings, similar to conventional subsonic commercial jet aircraft. The probable configuration is for two tanks in each wing, each containing about 35,000 pounds of fuel, and for two center tanks, each containing about 24,000 pounds of fuel, for a total fuel load of 183,000 pounds.

The tank configuration is similar to that shown in Figure A.8, even though it is for the L-1011-500 three-engine passenger transport. The line sizes and their exposure outside of the heavily protected structure are considered representative of the Jet A aircraft.

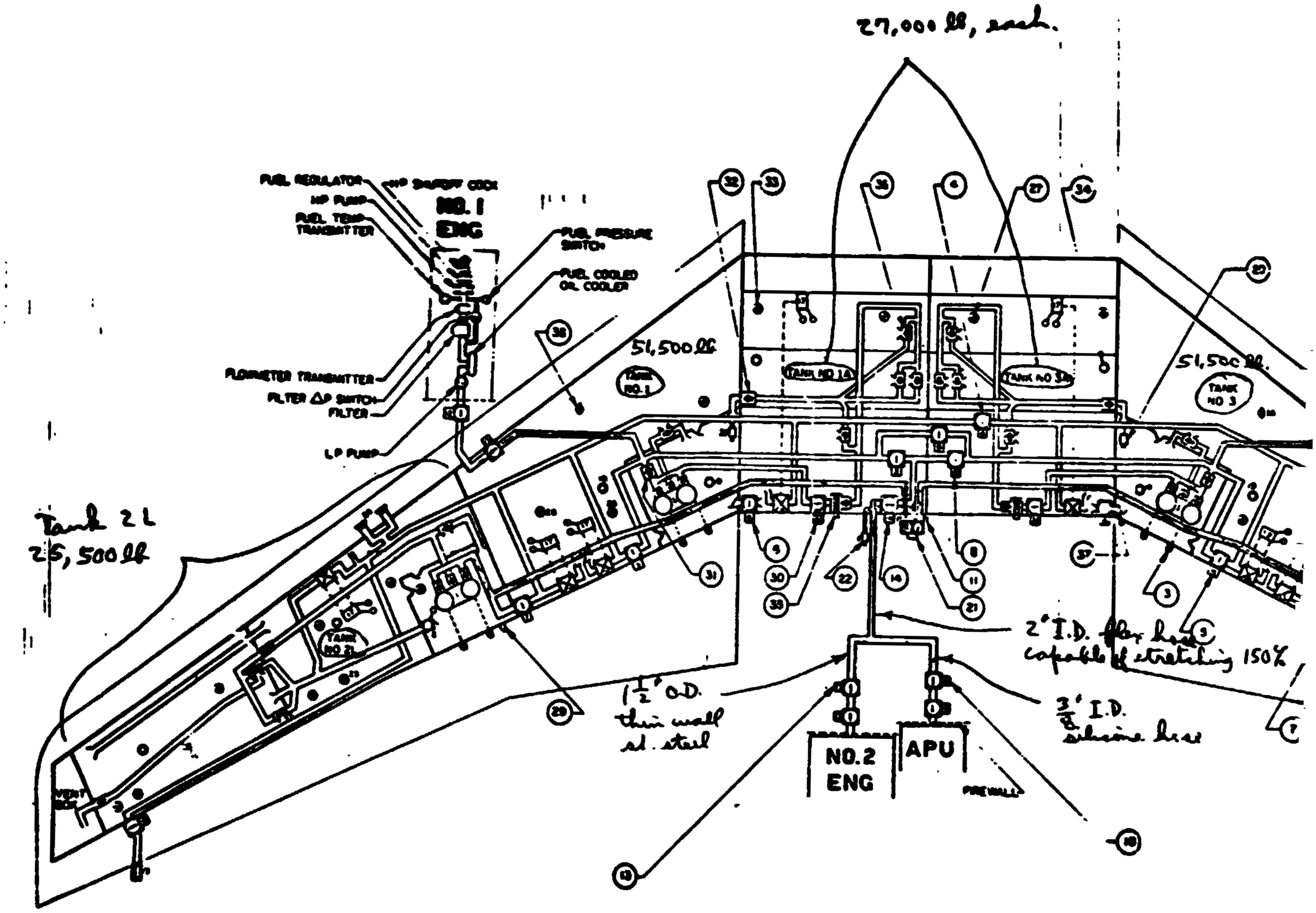
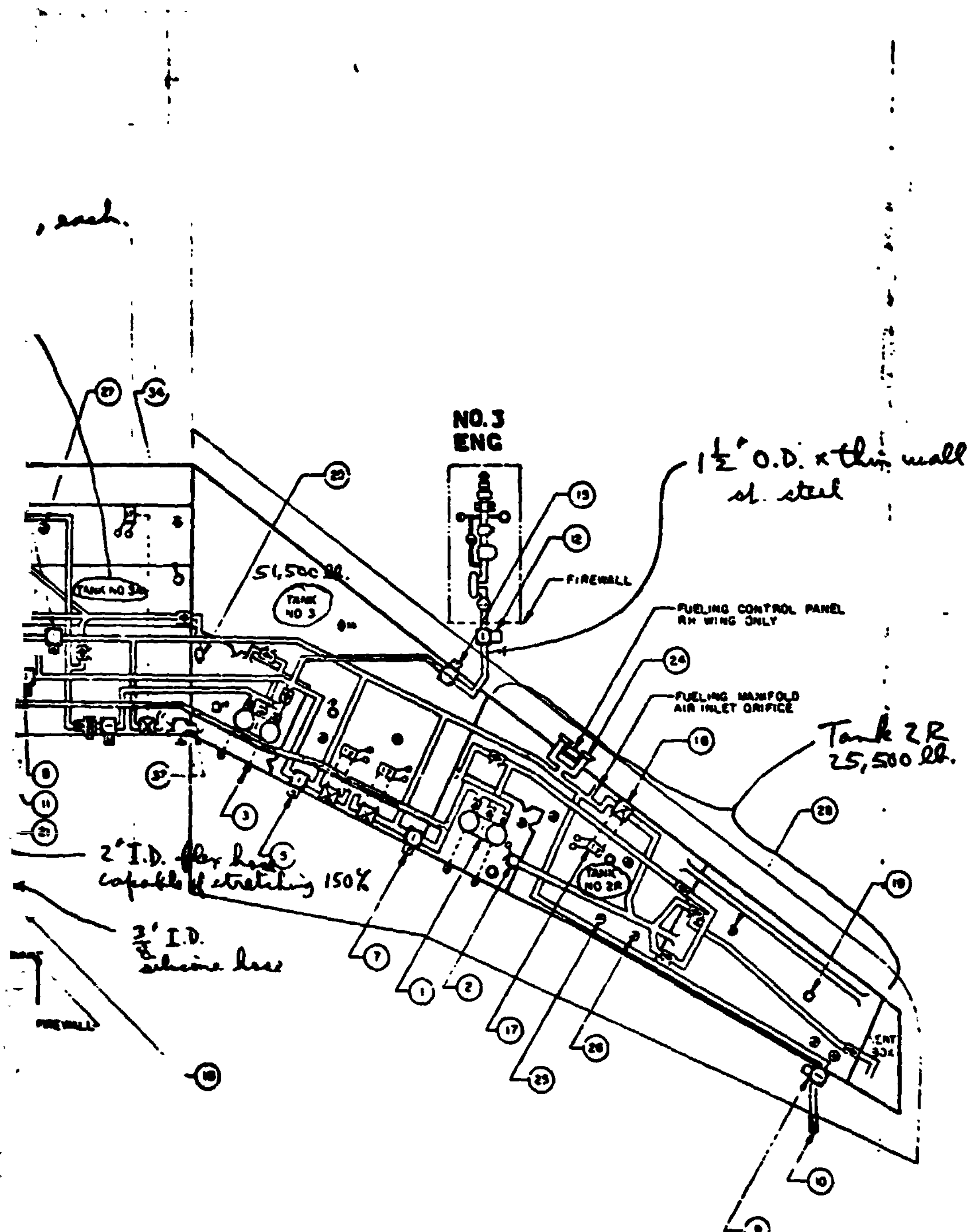


FIGURE A.8: JET A FUEL SYSTEM SCHEMATIC



38	LEVEL SENSING UNIT		741781-101	2
37	FLAPPER CHECK VALVE		741384-103	2
36	COMPOUND PUMP		672517-103	8
35	STRAINER-CHECK VALVE		673911-101	2
34	DRAIN VALVE		673482-101	2
33	GAGING PROBE ARRAY		671553	8
32	CHECK VALVE-TRANSFER LINE		673474-103	2
31	CHECK VALVE-FEED LINE		673474-103	2
30	TRANSFER & SCAVENGE [illegible] VALVE		673471-101	2
29	TEMPERATURE SENSOR		672015-101	1
28	GAGING PROBE ARRAY		671553	30
27	SIGHT GAGE-FUEL LEVEL		673362-101	2
26	SIGHT GAGE-FUEL LEVEL		671997	12
25	OVERWING GRAVITY FILLER			4
24	ADAPTOR PRESSURE FUELING		671819 -101 -102	2 2
23	CHECK VALVE-TRANSFER LINE		673474-101	2
22	SHUTOFF VALVE MANUALLY OPERATED (DRAIN AND TEST PORT)		673357-101	1
21	FLOW EQUALIZER		67 546-101	1
20	DRAIN VALVE FUELING MANIFOLD		672491-103	2
19	DRAIN VALVE		672001-103	10
18	SHUTOFF VALVE-APU LINE (FIREWALL)		671780-101	2
17	SWITCH-FUEL LEVEL CONTROL		67.801-107	9
16	SHUTOFF VALVE-FUELING		671802-107	9
15	ENGINE NO 1 & NO 3 TANK VALVE		672018-103	2
14	ENGINE NO 2 TANK VALVE		672018-101	1
13	SHUTOFF VALVE-MOTOR OPERATED (FIREWALL)		672011-101	2
12	SHUTOFF VALVE-MOTOR OPERATED (FIREWALL)		672011-103	2
11	SHUTOFF VALVE-NO 2 AND 2R TANK MANUALLY OPERATED		672912-101	2
10	FLAME ARRESTOR JETTISON		740367-101	2
9	SHUTOFF VALVE JETTISON		67250-101	2
8	CROSSFEED VALVE-MOTOR OPERATED		6720 3-101	3
7	SHUTOFF VALVE-DEFUELING		6720-7-103	2
6	GRAVITY INTERCONNECT-SO VALVE		67 996-105	2
5	SHUTOFF VALVE DEFUELING		671998-103	2
4	[illegible]		67-998 03	[illegible]
3	PRESSURE SWITCH-BOOST PUMP		672204-[illegible]	8
2	VALVE, [illegible] TRANSFER CONTROL		672757-[illegible]	2
1	BOOST PUMP WITH CHECK VALVES		67-543-21	4
[illegible]	NOMENCLATURE		[illegible]	[illegible]

SYSTEM SCHEMATIC

FOLDOUT FRAME 2

BOOSTER PUMPS

It is expected that each of the four wing tanks will contain two booster pumps, either of which can meet the fuel rate requirements of the assigned engine. These pumps are of the positive displacement type and have a capacity of about 20 pounds per second.

LINES

The booster pumps transfer the fuel from the tanks to their respective engines through 1.5 inch outside diameter, thin wall, uninsulated stainless steel tubing.

A.4.2 LINE BREAK

An engine pod torn off in a crash can cause fuel spillage. Assuming that the flight crew does not switch power off to the booster pump, it can deliver about 20 pounds per second from a severed 1.5 inch line. If power is switched off to the booster pumps, fuel can siphon from the tanks at rates depending upon fuel level, aircraft altitude and closure position of the tank shut off valve.

A.4.3 FUEL TANK LEAK

For crash landings in which the wings are severed and/or the fuselage is damaged in the wing-root area, it can be assumed that the onboard fuel is quickly released from containment. On the other hand, a tank punctured by a turbine blade released in an engine burst will dump fuel at a finite rate. For example, a 1.5 inch diameter puncture will release fuel at about 3 lb/sec. assuming a 2-foot static liquid height. For larger punctures, the fuel loss rate is proportional to the ratio of flow areas. These flow rates are summarized in Table 4.3 in Section 4.

A.5 REFERENCES

A.1 Brewer, G. D., et al, "Study of Fuel Systems for LH_2-Fueled Subsonic Transport Aircraft", Lockheed, Air Research and Rocketdyne, For NASA/Langley, July 1978, Volumes I and II.

A.2 Carson, L. K. et al, "Study of Methane Fuel for Subsonic Transport Aircraft", Lockheed, NASA Contractor Report 159320, September 1980.

A.3 Brewer, G. D., letter dated October 27, 1980 to F. Ruccia, "Crash Fire Hazard Study for NASA/Lewis."

APPENDIX B

CALCULATION OF EQUILIBRIUM CONDITIONS for H_2/AIR FLAMES

Using the NASA Equilibrium computer code*, we computed the temperature and water vapor concentration of the products of combustion for various concentrations of H_2/air burning at constant pressure. The results are shown in Figure B.1 for various levels of heat losses (as a fraction of the heat liberated). Note that the heat loss does not affect the predicted partial pressure of the water vapor (P_w) but affects the predicted temperature (T).

The horizontal dashed curves ($T = 1700^oK$ and $P_w = 0.25$ atm) indicate the approximate average values anticipated in view of nonuniformities in the hydrogen concentration within the flame. The temperature value is consistant with reported measurements. These values were used in the radiation calculations for hydrogen flames.

*NASA TN D-6586, 1972

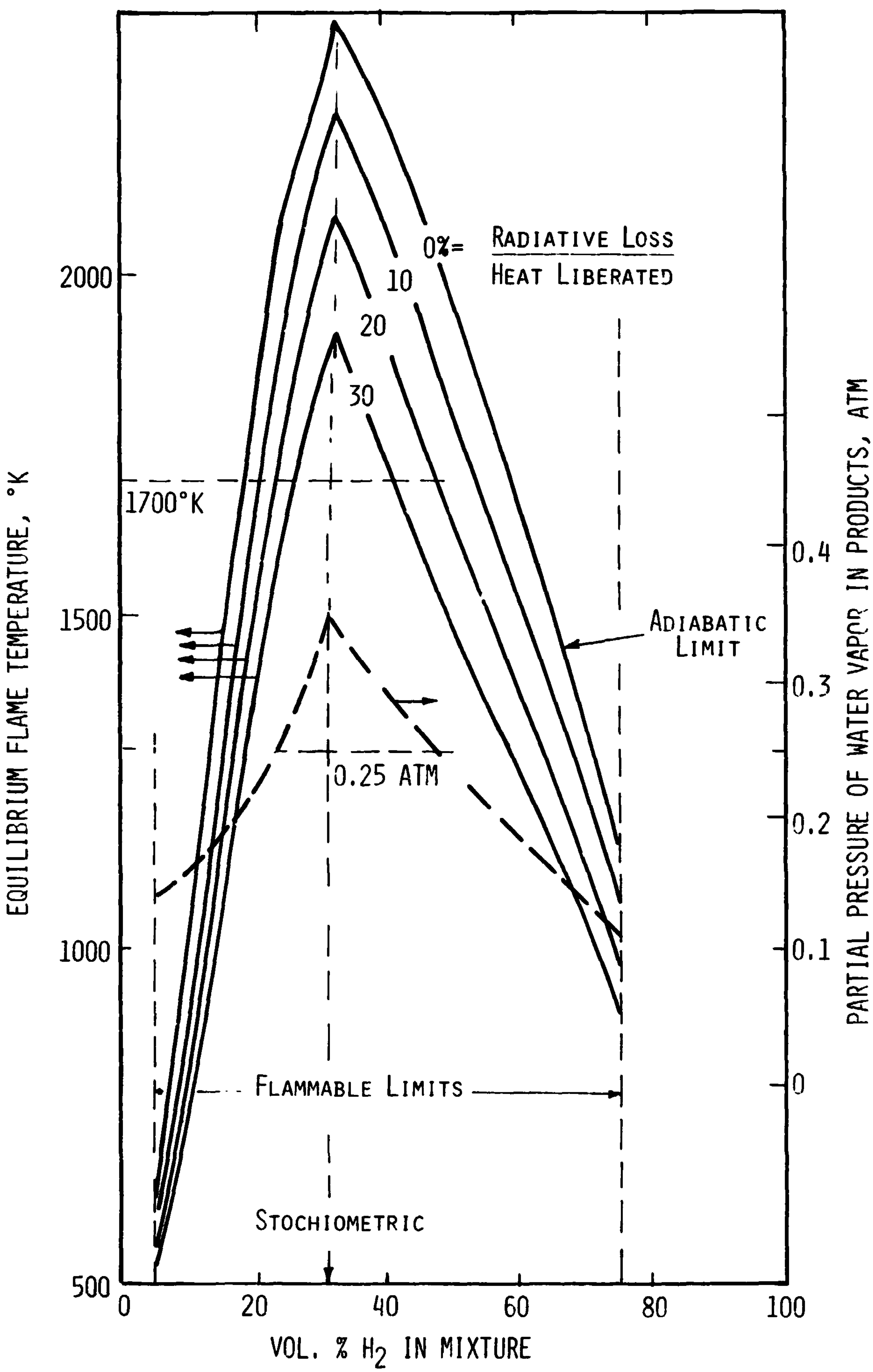


FIGURE B.1: EQUILIBRIUM CONDITIONS FOR CONSTANT PRESSURE COMBUSTION OF H_2/AIR MIXTURES WITH VARIOUS RADIATIVE HEAT LOSSES.

APPENDIX C

POOL FIRE DATA AND MODELS

C.1 INTRODUCTION

In this appendix, we present a review of the literature data and models pertinent to the characterization of pool fires. We focus on the burning rate, the pool diameter and the flame height. These three parameters are needed to determine the radiation hazards of pool fires.

First, we review of the experimental data on liquid pool boiling with and without combustion. These data are typically obtained for a constant pool diameter, fixed by the experimental setup. The parameters of most concern here is the liquid regression rate which is determined by heat transfer from the flame or from the substrate material under the liquid.

Secondly, we summarize the liquid spreading models utilized to determine the pool diameter of unconfined release on land. We cover both the instantaneous and continuous releases, with and without combustion.

Finally, we review the correlations in the literature on flame height and select the most suitable for use in our study.

C.2 EXPERIMENTAL DATA ON POOL BOILING

In a pool fire, the liquid boils due to heat transfer from either the flame or the ground (for cryogenic fuels) or both. Data has been compiled by many investigators for boiling with and without burning. These data are summarized in Table C.1 for LH_2, LCH_4 gasoline and kerosine. In each case, we describe briefly the experimental setup and give the volume of spilled liquid, the pool area, the substrate materials, the fuel, the liquid repression rate (with and without fire) and comments as appropriate. The substrate material is an important parameter since its thermal properties affect the rate of heat transfer to cryogens.

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TABLE C.1: SUMMARY OF LIQUID REGRESSION RATE ($\dot{y}$) DATA

Source	Description of Work	Amount Spilled m^3 of liquid	Pool Area m^2	Substrate Materials	Fuel	Liquid Regression Rate, mm/s Without Fire	Liquid Regression Rate, mm/s With Fire	Comments
ADL [C.1]	Various amounts were spilled in a diked are and ignited after various time delays	0.005-19	up to 58	Sand, bank gravel	LH_2	1.4-3.2* 0.5-0.8	~ Same as without fire	No increase in $\dot{y}$ for burning pools because of rate of heat feed-back from flame is equal to that of air condensation in non-burning pools.
Bureau of Mines [C.2,3]	Measured $\dot{y}$ for boiling in laboratory devices and field tests	up to 0.009	0.004	Paraffin wax, smooth macadam, sand and gravel	LH_2 LCH_4 Gasoline	up to 22* 0.04 to 0.9 0.009 to 0.09 0.001 to 0.0033	 0.5 to 1.1 0.05 to 0.2 0.033 to 0.15	Limiting value of it due to an optically thick H_2 flame is 0.25 mm/s
	Proposed the following correlation for steady state pool burning $\dot{y} = \dfrac{8.5 \times 10^{-4} \text{(Lower Heat Comb)}}{\text{(Liquid Density)} \cdot \text{(Eff. Latent Heat)}}$				LH_2 LCH$_4$ Gasoline Kerosine		3.2 0.2 0.08-0.15 0.08-0.106	Correlation does not account for heat trans-fer from substrate. Accordingly, it is poor for LH_2 and rich for gasoline.
Class et al [C.4]	LH_2 boiling in the nucleate and film boiling regimes on Karma surfaces (N_i 73%, C_r 20% + Al + Fe)			Rough/Smooth Gresed Karma	LH_2	up to 3.3		This value is for the film boiling regime.
AGA [C.5]	Most comprehensive LNG spills on land in dike area with and without fire	up to 50	2.5-468	Clay soil	LNG	0.08-0.1	0.15-0.23	Burning enhances $\dot{y}$ unlike the case of LH_2 contribution of flame = 1.4 × 10^{-4} m/s for an optically thick flame
Gas de France [C.6]	Large field spills in diked area	> 0.05	9-196	Soil	LNG	0.14		
NWC [C.7]	Large field tests of gasoline pool fires	45-181		Gasoline		-	0.08	
Raj [C.8]	Field tests of JP-4 pool fires in diked areas				JP-4		0.1	
Drake and Reid [C.9]	Laboratory tests without burning	6.4×10^{-4}- 9.5×10^{-4}	0.025	Soil at various temperatures	LNG	0.036-0.09	-	
Rohsenow [C.10,11]	Provided generalized correlations for the film heat transfer coefficient of cryogens				LH_2 LCH_4	4.6-10. 0.14-0.49		These are the maximum possible values limited only by heat transfer through a vapor film.
Witcofski [C.12]	Spills of 1500 gal over a period of 24 to 24 seconds	5.7	65	Compacted sand	LH_2	~2		It is calculated for a spill of 33 sec. and a total evaporation time of 45 sec.

*Initial state only.

TABLE C.2

SUMMARY OF LITERATURE DATA FOR POOL EVAPORATION

ITEM	LH_2	LCH_4	GASOLINE/JP-4	KEROSENE/JET A
Range of Liquid Regression Rate, mm/s				
No Fire	0.04 to 3.3	0.009 to 0.1	0.001-0.0033	Assumed same as gasoline
With Fire	Same as no fire*	0.05-0.23	0.033-0.17	0.08-0.106
Heat Transfer	Mainly from ground	From ground and flame	From flame only	From flame only

*We later found analytically that the flame contribution is very important for large fires.

The ranges of liquid regression data of Table C.1 are summarized in Table C.2 for LH_2, LCH_4, gasoline and kerosene. These data and our detailed review of the results summarized in Table C.1 indicate that the governing mode of heat transfer to the pool differs from fuel to fuel. This is also summarized in Table C.2.

The most systematic study of liquid hydrocarbon pool fires over the widest range of pool diameters was conducted by Blinov and Khudiakov (C.13). Gasoline, tractor kerosene, diesel oil, and solar oil (and, to a limited extent, household kerosene and transformer oil) were burned in cylindrical pans (depth not indicated) of diameters 0.37 cm. to 22.9 meters. Liquid burning rates and flame heights were measured, and visual and photographic observations of the flames were recorded.

Hottel (C.14), plotted the above data in Figure C.1. The lower curve of this figure gives the liquid burning velocity ($\dot{y}$) as a function of pan diameter (D); while the upper curve gives the flame height to pan diameter ratio. The diagonal lines are lines of constant Reynolds numbers (Re, based on pan diameter and the properties of non-burning fuel vapor).

It is of note that the burning velocity-pan diameter relation has the same general structure for all the fuels. It first decreases with increasing pan diameter, with an almost constant product of the two. This is the laminar flow regime, with Re less than about 20. With further increase in pan diameter the velocity reaches a minimum; then it rises rapidly in the range of Re from 20 to 200; and finally it levels off again at a pan diameter about 1 meter or a Reynolds number about 500. Above that value the burning is turbulent and the burning velocity is substantially uninfluenced by pan diameter or fuel type.

Hottel demonstrated that the above behavior can be related to the heat transfer rate ($\dot{q}$) that determine the rate of fuel vaporization:

$$\dot{q}/\frac{\pi d^2}{4} = \frac{4K}{d}(T_F - T_B) + H(T_F - T_B) + \sigma F(T_F^4 - T_B^4)(1 - e^{-\kappa d}) \qquad \text{C.1}$$

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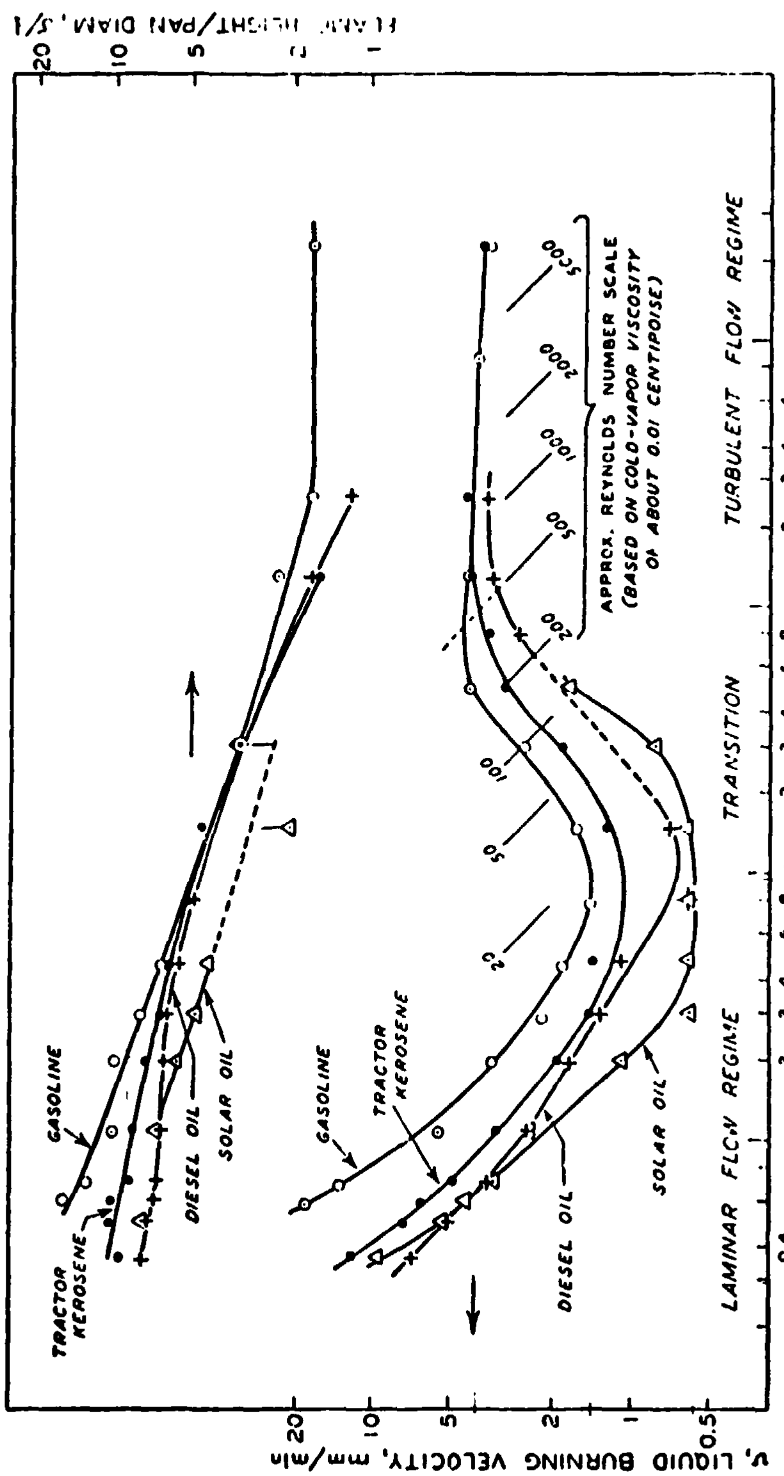

FIGURE C.1: CHARACTERISTICS OF LIQUID POOL FIRES (C.14)

where the left-hand side of the equation represents the mean heat flux to the liquid pool from the fire; the first term on the right represents the conductive heat transfer rate through the pan rim; the second term the convective heat flux; and the last term the radiative transfer rate. The mean heat flux to the pool divided by the heat of vaporization of the liquid gives the liquid burning rate ($\dot{y}$).

Hottel's review indicates that for heavy hydrocarbon fuels and a pool size greater than 1 m in diameter, the radiative heat transfer term dominates eg. C.1. Furthermore, the flame became optically thick. This is the regime of interest to steady large-scale, turbulent diffusion radiation-dominated pool fires.

A similar study of pool fires was also conducted at the Bureau of Mines (C.3), although over a smaller range of diameters. Still, they measured the limiting value of the burning rate for a number of liquid fuels and obtained the following correlation:

$$\underset{(cm/min)}{\dot{y}} = 0.0076 \frac{\Delta H_c''}{\Delta H_v} \qquad (C.2)$$

where $\dot{y}$ is the rate at which the liquid pool level decreases with time (in the absence of external supply), ΔH_c and ΔH_V are respectively the lower heat of combustion and the heat of vaporization of the liquid fuel (see Figure C.2).

In a later publication (C.2), the Bureau of Mines modified this correlation to include the fuel liquid density which varies significantly between the fuel studied.

C.3 MODELS OF POOL SPREADING WITH EVAPORATION

In this section, we present the result of a modeling study of the spreading of cryogenic liquids on land with and without heat transfer from a flame. The analysis is based mainly on the work of Raj. (C.15). Based on the liquid release rate and its duration, he classified the spills as: (1) 'instantaneous release' in which all of the spill occurs in a "very short time", and (2) the 'continuous spill' in which the spill continues at a finite rate for a "long time". The distinction

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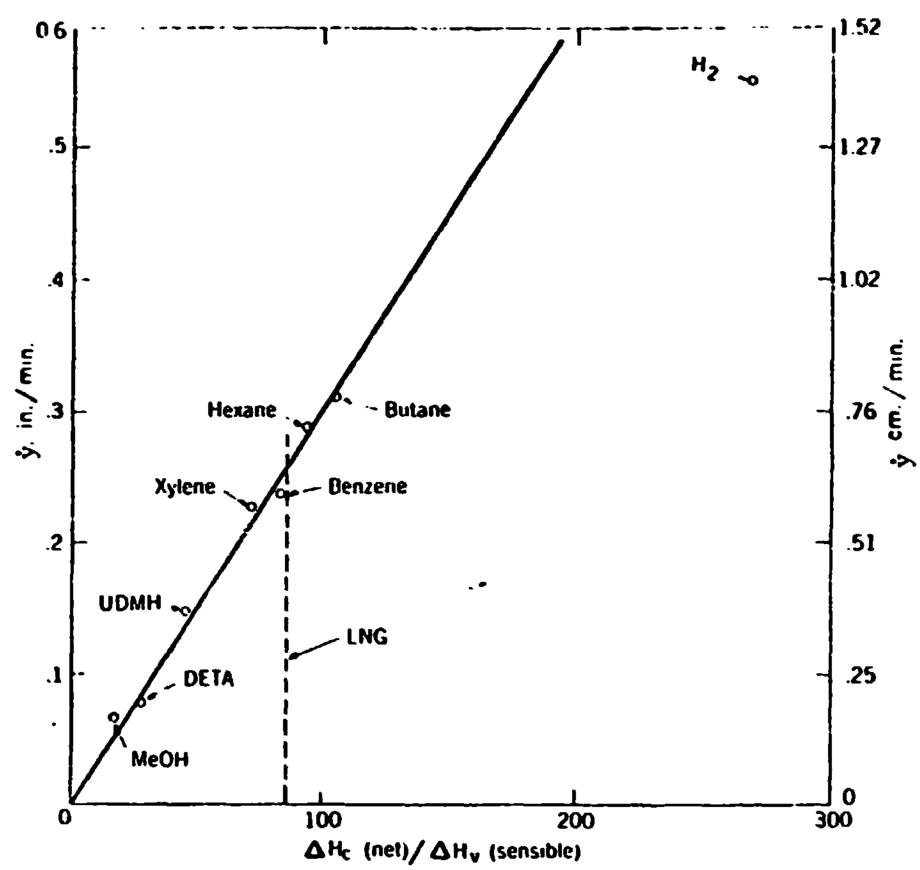

FIGURE C.2: RELATION BETWEEN BURNING RATES AND THERMOCHEMISTRY OF FUELS

between short time and long time depends on a number of factors including the size of spill, the properties of the liquid and the environmental conditions.

He formulated a mathematical model based on conservation of mass, momentum and energy, and on the following assumptions:

- The heat transfer rate from land can be obtained from quasi one-dimensional heat conduction theory.
- The ground is perfectly flat and frictionless.
- The diameter of the spill jet is small compared to the size of spread of liquid. That is, the source is a point source on the ground.
- The thermal boundary layer in the ground grows laterally because of the liquid spread and depthwise because of thermal propagation.
- Thermal boundary layer profiles are self similar at all times.
- A flame provides a constant heat flux to the pool.

He obtained expressions for the radius of spread, evaporation rate, and volume of liquid remaining as a function of time. His results for the case of heat transfer from ground alone and flame alone are summarized in Table C.3. Note that for cryogenic liquids, the pool radius increases continuously as the ground warms up. Thus, a steady pool may not be reached even for small continuous releases. The time dependence is weak, however, and a quasi-steady pool can be assumed.

These results were used to predict the pool diameters presented in Section 7 with the following items:

1) For LCH_4, gasoline and kerosene, we used the upper values of of the burning rate data in Table C.2 to determine the heat transfer from flame to pool.

TABLE C.3: SUMMARY OF LIQUID SPREADING MODELS FROM REFERENCE C.15

SPILL ENVIRONMENT	SPILL CHARACTERIZATION AND DETAILS	SCALING PARAMETERS LENGTH (L)	SCALING PARAMETERS TIME (t_{ch})	CHARACTERISTIC PARAMETER	SPREAD RADIUS VS. TIME RELATIONSHIP	MAXIMUM SPREAD RADIUS	MAXIMUM TIME FOR TOTAL EVAPORATION	REMARKS
1-D Transient Heat Conduction from Ground	CONTINUOUS SPILL AT VOLUMETRIC RATE $\dot{V}_L$	$L = \left[\frac{2}{\pi^{3/2}} \frac{\lambda \rho_L \dot{V}_L}{\sqrt{(k\rho c)_g}\,\Delta T}\right]^{\frac{1}{2}} t_{ch}^{\frac{1}{4}}$	t_{ch} CAN BE CHOSEN ARBITRARILY	–	$\xi = \tau^{1/4}$	–	–	$\xi = \frac{R}{L}$ $\tau = \frac{t}{t_{ch}}$ $\kappa = \frac{V}{V_L}$ $1 \le c \le \sqrt{2}$
	INSTANTANEOUS SPILL OF VOLUME V_L	$L = V_L^{\frac{1}{3}}$	$t_{ch} = \sqrt{\frac{L}{g}}$	$B = \left[\frac{\sqrt{\pi}}{2} \frac{\sqrt{(k\rho c)_g}\,\Delta T}{\lambda \rho_L \sqrt{t_{ch} g L}}\right]$	$\xi = [1.3\tau + 1.416\,\tau^{3/2}]^{\frac{1}{2}}$ $\kappa = [1 - 0.867\,B\tau^{3/2} - 0.472\,B^2\tau^3]$	$\xi_e = \frac{1.4507}{B^{\frac{1}{3}}}$	$\tau_e = \frac{0.864}{B^{2/3}}$	
Constant Heat Flux From Flame	CONTINUOUS SPILL AT VOLUMETRIC RATE $\dot{V}_L$	$L = R_{max} = \left[\frac{\dot{V}_L}{\pi \dot{y}}\right]^{\frac{1}{2}}$	$t_{ch} = \frac{L}{[c^2 g' L \dot{y}]^{\frac{1}{3}}}$	–	$\tau = 1.7938\, I_{\xi^2/2}(\frac{1}{3}, \frac{2}{3})$ $\kappa = (\frac{3}{4})^{2/3} \xi^{\frac{4}{3}} \left[1 - \frac{\xi^2}{2}\right]^{\frac{1}{3}}$	$\xi_e = 1$	$\tau_e = 0.897$	
	INSTANTANEOUS SPILL OF VOLUME V_L	$L = V_L^{\frac{1}{3}}$	$t_{ch} = \sqrt{\frac{L}{g'}}$	$D = \frac{\dot{y}}{\sqrt{g' L}}$	$\xi = [1.3\tau + 0.442\,\tau^3 D]^{\frac{1}{2}}$ $\kappa = 1 - 2.04\,D\tau^2 - 0.3473\,D^2\tau^4$	$\xi_e = \frac{1}{D^{\frac{1}{4}}}$	$\tau_e = \frac{0.6743}{D^{\frac{1}{2}}}$	$I_x(y, z)$ IS THE INCOMPLETE BETA FUNCTION.

Where;

T = Time From Spill Instant
R = Cloud Radius at t
V = Volume of Liquid Pool or Ground at t
λ = Heat of Vaporization
ρ = Liquid Density

r max = Maximum Cloud Radius
ΔT = Ambient Temperature - Boiling Point
$k\rho c_G$ = Thermal Inertia of Ground
g = Gravity Constant

2) For LCH_4 and LH_2 we also accounted for heat transfer from ground assuming a soil or concrete substrate.*

3) For LH_2, the heat transfer from the flame is not constant because the flame does not reach the optically thick limit within the fire sizes computed in this study. This requires an iterative solution since the heat transfer from the flame determines the pool size which in turn affect the heat transfer. We iterated accordingly to determine the LH_2 pool size presented in Section 7.

C.4 FLAME HEIGHT

Once the pool diameter and the liquid repression rate are determined as described in Section C.3, the flame height can be calculated using correlations obtained in the literature. Thomas (C.16) has developed a correlation for the mean visible height of turbulent diffusion flames (in the absence of wind), based on experimental data of laboratory-scale wooden crib fires and dimensional analysis considerations. The correlation for a circular fire is:

$$\frac{H}{D} = 42\left(\frac{\dot{m}''}{P_a\sqrt{g\,D}}\right)^{0.61} \qquad \text{C.3}$$

where $\dot{m}''$ is the mass burning rate per unit pool area.

The analysis of Thomas, based on which the above correlation has been developed, makes some fundamental assumptions. The flame is characterized by a single temperature and a specified gas composition at the flame tip irrespective of the size or soot concentration in the flame. The correlation does not take into account either the differences in the fuel properties, or the differences in their flame radiation characteristics. In addition, Thomas indicates that the correlation is valid only if the turbulence is generated by the heat source itself, and not if ambient turbulence is convected into the fire plume. While it is true that Thomas has successfully correlated small, laboratory-size fire data, the validity of his correlation for large fires ($D > 25$ m) has never been tested. Figure C.3 shows the data on visible fire lengths observed in the AGA tests (C.5). Also shown is the above correlation.

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*$\sqrt{k\rho c} = 1.4\ \mathrm{kJ/m^2\,.\,^oK.s^{0.5}}$

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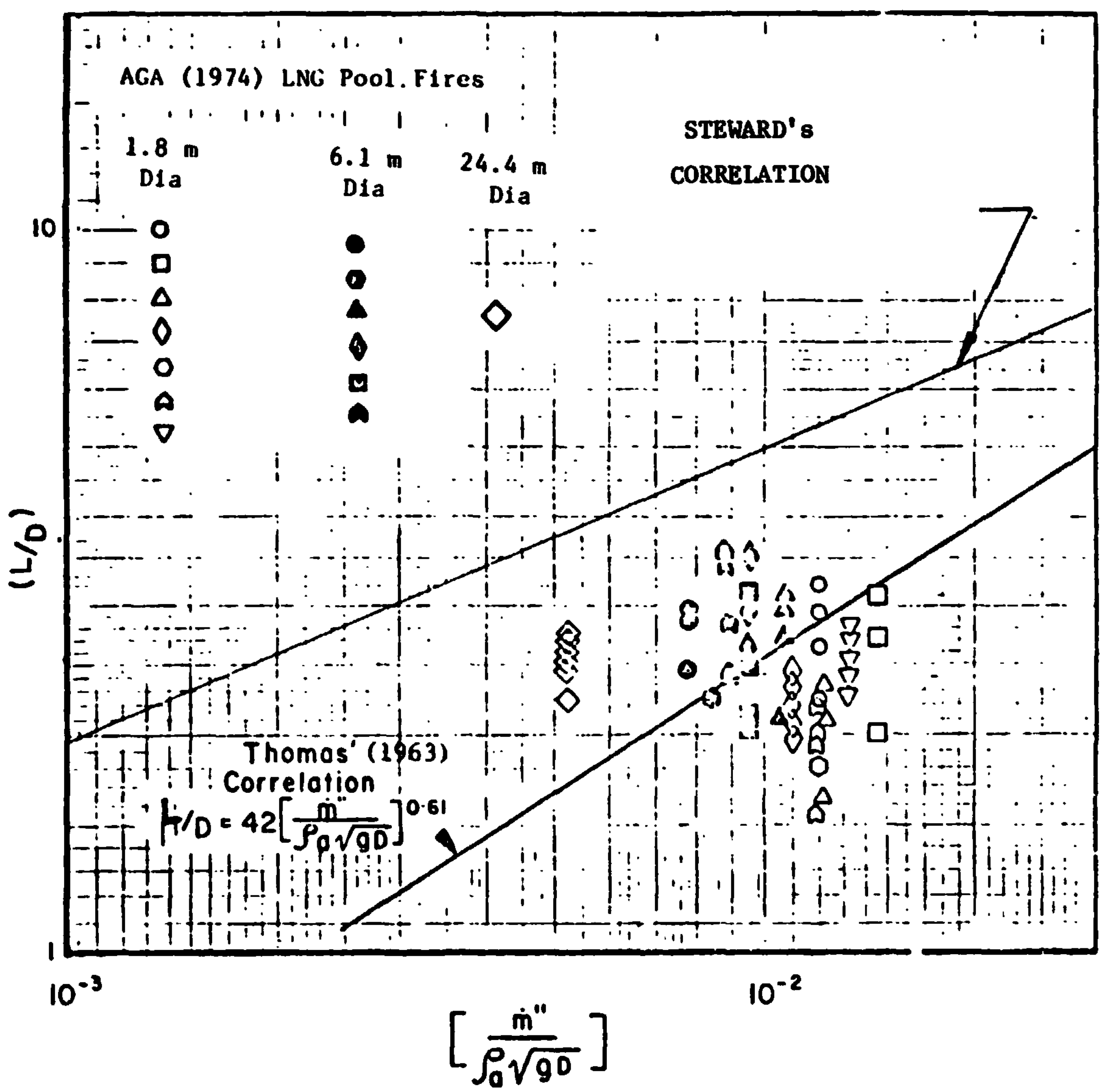

FIGURE C.3 LNG: Flame height data from experiments and comparison with correlations from the literatere (C.5)

It is seen that the correlation generally underpredicts the height (by up to 50%) for large-diameter fires (larger than 6 m).

The applicability of Thomas' correlation for higher hydrocarbon fuels is shown in Figure C.4. The measured values are for JP-4 pool fires of diameters varying from 1 to 10 m (C.17). The correlation is obtained from eg. (C.3) with $\dot{m}'' = 0.05$ kg/m^2.s (or a linear regression rate of 4 mm/min).

Steward (C.18) has also developed a similar correlation which is plotted in Figure C.3. As can be seen from the figure, Thomas' correlation provides a better fit of the data than Steward's. Accordingly, it has been used throughout our calculations.

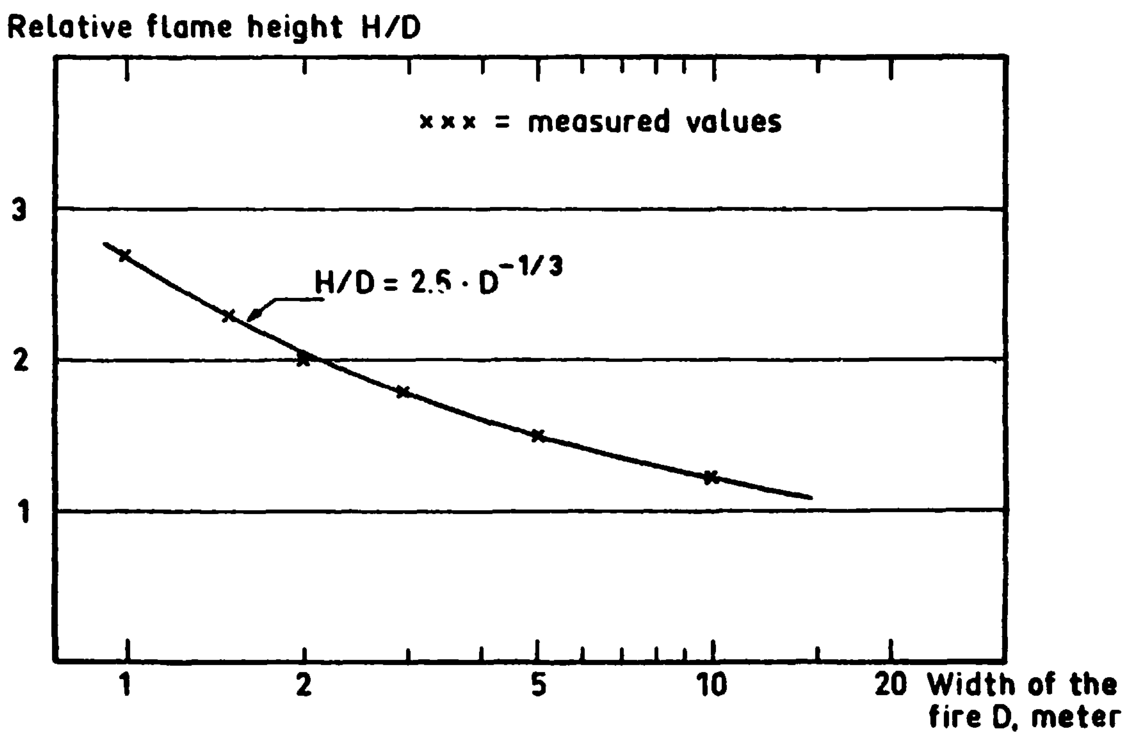

FIGURE C.4: RELATIVE FLAME HEIGHT (H/D) AS A FUNCTION OF FIRE WIDTH (D) FOR JP-4 POOL FIRES (C.17)

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